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Bolted Connections in Cold Formed Steel Structures

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FINAL REPORT

BOLTED CONNECTIONS IN COLD-FORMED STEEL STRUCTURES

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I. INTRODUCTION

A. PURPOSE OF INVESTIGATION

Bolted connections are usually designed for cold-formed steel structures in accordance with Section 4.5 of the AISI Specification for the Design of Cold-Formed Steel Structural Members.(1) These design provisions were originally developed on the basis of the Cornell tests,(3,4,13) for which all bolts used in the connections were tightened to the specified torques, and washers were always placed under the head and nut of each bolt.

In recent years, bolts without washers are often used in cold-formed steel structures. In some cases, even though washers are used with the bolts, the bolts may not be tightened to the specified torques used in the tests. For this reason, the original design provisions of the AISI Specification(1) may not be applicable either to bolts used without washers or to bolts installed with the torques less than that used in the tests.

The purpose of the investigation reported herein was to develop the background information needed for the revision of the AISI Specification.(1) The new design provisions for bolts without washers and bolts installed with less than the specified torques are included in the 1980 Edition of the Specification.(22) During the revision of the AISI design criteria, due consideration was given to the available research results recently published by other investigators (2, 6,10-18) and the additional experimental work conducted during the project.(19-21)

B. SCOPE OF INVESTIGATION

To reach the project's research objectives, the following tasks have been conducted at the University of Missouri-Rolla since 1976:

(a) literature review and analysis of available test data,

(b) study of the effects of torques and washers on the bearing strength and shear strength of connected parts,

(c) experimental work for the development of installation procedures for bolts, and

(d) preparation of revised design recommendations.

The details of the various studies have been presented in three progress reports, which are reproduced in the Appendix of this final report. A summary of these three progress reports is given in Article II.

The revised AISI bolted connection design criteria included in the 1980 Edition of the Specification for the Design of Cold-Formed Steel Structural Members are presented in Article III. The reasoning behind and justification for these new revisions are documented in Article III. C.

Finally, Article IV is a summary of the entire study.

II. SUMMARY OF PROGRESS REPORTS

During the period of June 1976 through August 1978, three progress reports on bolted connections in cold-formed steel structures were prepared by researchers at the University of Missouri-Rolla. They were submitted to American Iron and Steel Institute for development of the revised design provisions, which are included in Article III. B. These three reports are summarized below. For details, the reader should consult the Appendix.

A. FIRST PROGRESS REPORT

This report presents a review of the available test data on bolted connections and a study of the additional design provisions needed for the 1968 Edition of the AISI Specification concerning minimum edge distance, allowable tension on net section, allowable bearing between bolts and connected parts, and allowable shear stress on bolts.

It was found that the F_u/F_y ratio (F_u being the ultimate tensile strength and F_y being the yield point of steel sheets) affects considerably the bearing strength of bolted connections and the shear strength of steel sheets in the line of stress particularly when $F_u/F_y < 1.35$. For connections with the same geometric configurations, the smaller the F_u/F_y ratio, the lower the bearing strength.

The study of d/t ratios versus strengths of bolted connections indicates that in general the d/t ratio has little or no effect on (a) the bearing strength of bolted connections, (b) the longitudinal shear strength of steel sheets, and (c) the tensile strength of a net section.

The study of connections bolted without washers that was recently conducted by Chong, Matlock, and Gilchrist indicates that the washers play an important role in the bearing and tensile strength of connections.[11,15]

B. SECOND PROGRESS REPORT

This report deals with the experimental work conducted at the University of Missouri-Rolla on (a) bolt installation and (b) the effects of torque and washers on the shear and bearing capacity of bolted connections composed mainly of materials thinner than 0.036 inches.

(a) Bolt Installation

The purpose of this experimental work was to develop a turn-of-nut method for bolted connections composed of cold-formed steel members and to determine the bolt tension resulting from the torque values used in the original Cornell study. Based on the results of 25 pretension tests, it was found that from a finger-tight position, the specified minimum pretension can be reached by a nut rotation of 240 degrees for the 1/2 in. diameter A325 bolts and of 270 degrees for the 5/8 in. diameter bolts. The change of grip lengths of the connections was found to have little effect on the nut rotation required for reaching the specified minimum pretension. It was also found that the torque values used in the original Cornell study provide sufficient pretension as compared with those specified by the Research Council on Structural Connections and American Institute of Steel Construction [2,6].

(b) Study of Effects of Torques and Washers on the Strength of Bolted Connections

The second part of this report presents the results of 50 tests conducted at the University of Missouri-Rolla in the summer of 1976. This additional study deals with the effects of torques and washers on the bearing and shear strengths of single shear and double shear connections composed of thin materials.

This study indicates that the shear capacity of thin sheets in line with the applied load is not affected by the use of washers and that the ultimate bearing stress can be determined accurately in terms of the ultimate tensile strength, F_u, instead of the yield point of sheet steel, F_y. Two separate design formulas were proposed in the report for connections made by bolts with and without washers. It was found that for lap joints composed of materials less than 0.036 in. in thickness the elimination of washers results in a substantial reduction in the bearing strength of the connection. This is due to the bolts' excessive rotation, which causes a premature failure.

C. THIRD PROGRESS REPORT

This report presents the results of 370 additional tests for a study of the bearing strength of bolted connections affected by the amount of torque used in installation. The test specimens used in the UMR tests fabricated from two types of bolts. Three different bolt diameters and seven different types of steel sheets with various mechanical properties were also used. Three different torques were employed to install the bolts with and without washers.

The study indicates that for some types of bolts with large d/t ratios the bearing strength of the connections may be affected by the amount of torque actually used in the installation. The use of washers can improve considerably the bearing strength of lap joints. For the inside sheet of butt joints, the effect of washers is less important.

The test data indicate that when structural bolts are installed by using the low torques same as that used for installation of A307 bolts, satisfactory performance can be expected as far as the bearing capacity of the connection is concerned. The design requirements for minimum edge distance, minimum spacing, tensile capacity of the net section, and the shear strength of the bolts are not affected by the initial clamping force.

III. BASIS FOR THE REVISION OF THE AISI DESIGN CRITERIA

A. GENERAL

In late 1974, the AISI Advisory Group on the Specification for the Design of Cold-Formed Steel Structural Members appointed Submommittee 3 to study the possible revision of Section 4.5 of the Specification for the design of bolted connections. The major revision of Section 4.5 was completed in 1978 by a joint effort of Subcommittee 3 of the AISI Advisory Group, AISI Task Group on Bolted Connections of the Engineering Subcommittee of the Sheet Committees, and Committee 27 of the Research Council on Structural Connections. The revised design provisions are included in the 1980 Edition of the AISI Specification.(22)

Compared with the 1968 Edition of the AISI Specification,(1) the revised design provisions(22) include the following major additions and changes:

a. In a new subsection on materials, references are made to the use of A490, A449, and A354, Grade BD bolts in addition to A307 and A325 bolts.

b. A new section on bolt installation is added.

c. The design provisions for minimum spacing and edge distance are based on F_u instead of F_y.

d. The allowable tension stress and bearing stress are determined on the basis of F_u instead of F_y. New design formulas are added for connections bolted without washers.

e. The allowable shear stresses on bolts are increased in accordance with the Specification for Structural Joints Using ASTM A325 and A490 Bolts of the Research Council on Structural Connections.

The revised Section 4.5 is presented in Article III.B. Article IV.C contains detailed comments on the revised AISI design criteria along with necessary background information.

B. SECTION 4.5 OF THE AISI SPECIFICATION

The following revised design provisions are now included in Section 4.5 of the AISI Specification for the Design of Cold-Formed Steel Structural Members, 1980 Edition:

"4.5 BOLTED CONNECTIONS

4.5.1 Scope

The following requirements govern bolted connections of cold-formed steel structural members in which the thickness of the thinnest connected part is less than 3/16 inch. For bolted connections in which the thinnest connected part is equal to or greater than 3/16 inch, refer to AISC's "Specification for the Design, Fabrication and Erection of Structural Steel for Buildings," November 1, 1978.

4.5.2 Materials

Bolts, nuts, and washers shall generally conform to one of the following specifications

- Carbon Steel Externally and Internally Threaded Standard Fasteners, ASTM A 307-78, Type A
- High-Strength Bolts for Structural Steel Joints, ASTM A 325-79
- Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners, ASTM A 354-79, Gr. BD (for diameter of bolt smaller than 1/2 in.)
- Quenched and Tempered Steel Bolts and Studs, ASTM A 449-78a (for diameter of bolt smaller than 1/2 in.)
- Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints, ASTM A 490-79

When other than the above are used, drawings shall indicate clearly the type and size of fasteners to be employed and the allowable stresses assumed in design.

4.5.3 Bolt Installation

Bolts shall be installed and tightened to achieve satisfactory performance of the connections involved under usual service conditions.

4.5.4 Minimum Spacing and Edge Distance in Line of Stress

The distance e measured in the line of force from the center of a standard hole* to the nearest edge of an adjacent hole or to the end of the connected part toward which the force is directed shall not be less than the value of e_{min} determined below:

(a) When $F_u/F_y \geq 1.15$:

$$e_{min} = \frac{P}{0.5\ F_u t} \qquad \text{(Eq. 4.5.4-1)}$$

(b) When $F_u/F_y < 1.15$:

$$e_{min} = \frac{P}{0.45\ F_u t} \qquad \text{(Eq. 4.5.4-2)}$$

where

P = force transmitted by bolt, kips

t = thickness of thinnest connected part, in.

F_u = specified minimum ultimate tnesile strength of steel of the connected part, ksi

F_y = specified minimum tensile yield point of steel of the connected part, ksi

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*The diameter of a standard hole is 1/16 in. larger than the bolt diameter for 1/2 in. and larger bolts, and is 1/32 in. larger than the bolt diameter for bolts less than 1/2 in. in diameter.

In addition, the minimum distance between centers of bolt holes shall provide sufficient clearance for bolt heads, nuts, washers and the wrench but shall not be less than 3 times the nominal bolt diameter, d. Also, the distance from the center of any standard hole to the end or other boundary of the connecting member shall not be less than 1-1/2 d.

For oversized and slotted holes, the distance between edges of two adjacent holes and the distance measured from the edge of the hole to the end or other boundary of the connecting member in the line of stress shall not be less than the value of $[e_{min} - (d_h/2)]$, in which e_{min} is the required distance computed from the applicable equation given above, and d_h is the diameter of a standard hole defined in the footnote of this section. In no case shall the clear distance between edges of two adjacent holes be less than 2d and the distance between the edge of the hole and the end of the member be less than d.

4.5.5 Tension Stress on Net Section

The tension stress on net section of a bolted connection shall not exceed 0.6 F_y nor shall it exceed the following allowable stress:

(A) When $t \geq 3/16$ in.:

See Section 4.5.1

(B) When $t < 3/16$ in.:

(a) With washers under both bolt head and nut

(i) Double shear connection

$$F_t = (1.0 - 0.9r + 3rd/s)0.50\ F_u < 0.50\ F_u \qquad \text{(Eq. 4.5.5-1)}$$

(ii) Single shear connection

$$F_t = (1.0 - 0.9r + 3rd/s)0.45\ F_u < 0.45\ F_u \qquad \text{(Eq. 4.5.5-2)}$$

(b) Without washers under both bolt head and nut, or with only one washer

$$F_t = (1.0 - r + 2.5rd/s)0.45\ F_u < 0.45\ F_u \qquad \text{(Eq. 4.5.5-3)}$$

where

r = the force transmitted by the bolt or bolts at the section considered, divided by the tension force in the member at that section. If r is less than 0.2, it may be taken equal to zero.

s = spacing of bolts perpendicular to line of stress, in. In the case of a single bolt, s = width of sheet

F_t = allowable tension stress on net section, ksi

F_u, F_y, d, and t are defined in Section 4.5.4.

4.5.6 Bearing Stress in Bolted Connections

The bearing stress on the area (d x t) shall not exceed the allowable stress given in Tables 4.5.6 (A) and 4.5.6 (B), where F_p is the allowable bearing stress, ksi. F_u and F_y are defined in Section 4.5.4. For conditions not shown, stresses shall be determined on the basis of test data using a factor of safety of 2.22.

TABLE 4.5.6 (A)

Allowable Bearing Stresses for Bolted Connections

with Washers under Both Bolt Head and Nut

Thickness of connected part (inches)	Type of joint	F_u/F_y ratio of connected part	Allowable bearing stress, F_p (ksi)
$\geq$ 0.024 but < 3/16	Inside sheet of double shear connection	$\geq$ 1.15	1.50 F_u
		< 1.15	1.35 F_u
	Single shear and outside sheets of double shear connection	No limit	1.35 F_u
$\geq$ 3/16	See Section 4.5.1		

TABLE 4.5.6 (B)

Allowable Bearing Stresses for Bolted Connections without Washers under Both Bolt Head and Nut, or with only One Washer

Thickness of connected part (inches)	Type of joint	F_u/F_y ratio of connected part	Allowable bearing stress, F_p (ksi)
$\geq$ 0.036 but < 3/16	Inside sheet of double shear connection	> 1.15	1.35 F_u
	Single shear and outside sheets of double shear connection	> 1.15	1.00 F_u
> 3/16	See Section 4.5.1		

4.5.7 Shear Stress on Bolts

The shear stress on the gross cross-sectional area of bolts designed for dead and live loads shall not exceed the following values:

(a)	ASTM A307-78 Bolts, Type A	10 ksi
(b)	ASTM A325-79 Bolts	
	When threading is excluded from shear planes	30 ksi
	When threading is not excluded from shear planes	21 ksi
(c)	ASTM A354-79 Grade BD Bolts (less than 1/2 in. in diameter)	
	When threading is excluded from shear planes	40 ksi
	When threading is not excluded from shear planes	24 ksi
(d)	ASTM A449-78a Bolts (less than 1/2 in. in diameter)	
	When threading is excluded from shear planes	30 ksi
	When threading is not excluded from shear planes	18 ksi
(e)	ASTM A490-79 Bolts	
	When threading is excluded from shear planes	40 ksi
	When threading is not excluded from shear planes	28 ksi

C. COMMENTS ON SECTION 4.5 OF THE AISI DESIGN SPECIFICATION

In the 1980 Edition of the AISI Specification, Section 4.5 was extensively revised to reflect the results of a recent study and to provide a better coordination with the specifications of the Research Council on Structural Connections and the American Institute of Steel Construction.[2,6] In the revised Section 4.5, three new subsections were added for scope, materials, and bolt installation. The subsections used in the 1968 Edition of the Specification were revised and renumbered.

In the following discussion, the numbers of the subsections are the same as those used in the 1980 Edition of the Specification.

4.5.1 Scope

During the revision of Section 4.5 of the Specification, due consideration was given to the range of thicknesses (0.012 in. to 1 in.) of steel sheets, strip, flat bars, and plates, which are generally used for fabricating cold-formed steel structural members. In addition, the effect of the mechanical properties of the connected parts and bolts on the strength of bolted connections was carefully evaluated and incorporated in the revision.

Because previous studies and past practical experience have indicated that the structural behavior of bolted connections used for joining relatively thick cold-formed steel members is similar to that of connected hot-rolled shapes and built-up members, the revised Section 4.5 is applicable only to cold-formed steel members that are less than 3/16 inch in thickness. For materials not less than 3/16 in., the AISC design provisions can be used for the design of bolted connections in cold-formed steel structures.

4.5.2 Materials

In Section 4.5.4 of the 1968 Edition of the AISI Specification, the allowable shear stresses are provided only for A307 and A325 bolts. Because the maximum thickness for cold-formed members has been increased from 1/2 in. to 1 in., other high-strength bolts, such as A354, A449, and A490 bolts have been included in the new subsection for bolted connections.

It should be noted that A325 and A490 bolts are available only for a diameter of 1/2 in. and larger. High-strength A449 and A354 Grade BD bolts should be used as equivalents of A325 and A490 bolts, respectively, whenever smaller bolts (less than 1/2 in. in diameter) are required in a design.

For other types of fasteners, which are not listed in this section, the allowable stresses should be determined by tests in accordance with Section 6 of the AISI Specification.

4.5.3 Bolt Installation

This is a new subsection of the revised specification. Even though no specific requirements are given for installation, bolts should be properly tightened according to good practice used in building construction.

The method of installation and the effect of torques on the strength of bolted connections have been studied and reported in Refs. 15 and 16. This background information will be useful for future development of installation procedures.

It should be noted that the required pretension in bolts varies with the types of connected parts, fasteners, applied loads, and applications. It may be found that it is unnecessary for the AISI Specification to include specific requirements for bolt installation.

4.5.4 Minimum Spacing and Edge Distance in Line of Stress

In Section 4.5.1 of the 1968 Edition of the AISI Specification, the minimum spacing and edge distance in line of stress are determined by the following two requirements:

$$e_{min} = 1.5d \tag{c1}$$

$$e_{min} = P/(0.60\ F_y t) \tag{c2}$$

in which e_{min} is the required minimum spacing and edge distance in line of stress, in., d is the diameter of bolts, in., P is the allowable load transmitted by one bolt, kips, F_y is the yield joint of connected parts, ksi, and t is the thickness of the thinest connected part, in.

In the revised specification, the first requirement, Eq. (c1), is considered to be a general criterion. The second requirement, Eq.(c2), was changed to Eqs. (c3) and (c4) below on the basis of the longitudinal shearing capacity of connected parts.

When $F_u/F_y \geq 1.15$

$$e_{min} = P/(0.5\ F_u t) \tag{c3}$$

When $F_u/F_y < 1.15$

$$e_{min} = P/(0.45\ F_u t) \tag{c4}$$

The above two formulas are Eqs. (4.5.4-1) and (4.5.4-2) of the revised specification respectively.

It can be seen that Equations (c3) and (c4) were derived from Eq. (c5) with a safety factor of 2.0 for $F_u/F_y \geq 1.15$ and 2.22 for $F_u/F_y < 1.15$.

$$e_{min} = \frac{P}{F_u t} \tag{c5}$$

The above equation is based on the relationship with Eq.(c6) which was established on the test data.

$$\sigma_b/F_u = e/d \tag{c6}$$

In Eq.(c6), σ_b is the ultimate bearing stress between the bolt and steel sheet, ksi. The correlations between the test data and Eq.(c6) are shown in Figs. 1 and 2 for $F_u/F_y \geq 1.15$. Figures 3 and 4 show the graphic comparison of the test data and Eq.(c6) for $F_u/F_y < 1.15$. The specific F_u/F_y ratio of 1.15 represents the lowest value for the structural steels listed in the AISC Specification.[6] It should be noted that Figs. 1 and 3 are for the case of single shear connections (lap joints), whereas Figs. 2 and 4 are for the case of double shear connections (butt joints). These figures indicate the justification for using a larger safety factor for the case of $F_u/F_y < 1.15$.

The dimensions of the test specimens and details of the test data used for plotting Figs. 1 through 4 are presented in Tables 1 through 4 respectively.

It should be noted that Eq.(c6) has been used in the Specifications of the Research Council on Structural Connections and the American Institute of Steel Construction.[2,6] Therefore, the revised AISI requirement for minimum edge distance is the same as that required by the AISC and Research Council Specifications when $F_u/F_y \geq 1.15$.

Comparisons of the revised provision (1980) for minimum edge distance, the 1968 AISI Specification, and the AISC Specification are presented in Table A. It can be seen that for the 12 types of steels used in the comparisons, the revised provision permits the use of relatively small edge distances as compared with the 1968 Edition of the AISI Specification. However, when $F_u/F_y < 1.15$, the revised provision and the 1968 Specification require about the same amount of edge distance.

For the case of single shear connections without washers, the test data shown in Figs. 11 and 12 together with the results given in Tables 11 and 12a verify the validity of Eq.(c6).

In addition to the changes discussed above, several new requirements have been added to the revised criteria concerning (a) the minimum distance between the centers of holes as required for the installation of bolts, (b) the required distance between the edges of two adjacent holes, and (c) the minimum distance between the edge of a hole and the end of a member. Most of these newly added requirements are based on the general practices applied in cold-formed steel construction.

4.5.5 Tension Stress on Net Section

In the revised provisions, the design formula used for computing the allowable tension stress, F_t, on the net section of connected parts has been changed as follows:

1. The provisions are applicable only to the thinnest connected part, which is less than 3/16 in. thick. For thick materials, i.e. $t \geq 3/16$ in., one can determine the allowable tension stress by using the AISC Specification.(6)
2. The allowable tension stress for the net section of a connected member is determined by the tensile strength of the connected part (F_u) instead of the yield point of steel (F_y).
3. Different formulas are given for bolted connections with and without washers.
4. The allowable tension stress for the net section of a connected member is based on the type of joint, either a single shear lap joint or a double shear butt joint.

For connections in which washers are placed under both the heads and nuts of the bolts, the equations for computing the allowable tension stress (Eqs.(4.5.5-1) and (4.5.5.5-2),were derived from the following formula for the ultimate tensile stress, σ_{net}, with the proper factors of safety.

$$\sigma_{net} = (1.0 - 0.9r + 3rd/s)\ F_u \leq F_u \qquad \text{(c7)}$$

In the above equation, σ_{net} is the ultimate tensile stress on the net section, ksi, s is the spacing of bolts perpendicular to the line of stress, in., and r is a ratio of the force transmitted by the bolt or bolts at the section considered, divided by the tension force in the member at that section. The factors of safety used for deriving Eq. (4.5.5-1) for double shear connections and Eq. (4.5.5-2) for single shear connections are 2.0 and 2.22 respectively.

The correlation between Eq. (c7) and the test data presented in Table 5 is shown graphically in Fig. 5.

When washers are not used and when only one washer is used in bolted connections, the ultimate tensile stress on the net section, σ_{net}, can be determined by Eq. (c8):

$$\sigma_{net} = (1.0 - r + 2.5r\ d/s)\ F_u \leq F_u \qquad \text{(c8)}$$

Equation (4.5.5-3) of the revised Specification was derived from the above formula by using a safety factor of 2.22. Figure 6 shows the correlation between Eq. (c8) and the test data presented in Table 6.

Comparisons of the revised specification (1980), the 1968 AISI Specification, and the AISC Specification are given in Tables A and B. It is of interest to note in Table B that for single shear connections the revised equation is practically the same as the formula used in the 1968 AISI Specification with an exception for A36 steel. For double shear connections, the revised equation gives an allowable tension stress about 13% higher than that permitted by the 1968 Edition of the AISI Specification.

4.5.6 Bearing Stress in Bolted Connections

In Section 4.5.6, the determination of the allowable bearing stress has been extensively revised.

Based on the study conducted in this project, it was found that the bearing strength of bolted connections depends on the tensile strength of the connected part, the thickness of the connected part, the type of joints (lap joint or butt joint), the F_u/F_y ratio, and the use of washers. Tables C-1 and C-2 list the formulas for predicting the ultimate bearing strengths of bolted connections. They were derived from the test data shown in Figs. 7 through 14 and presented in Tables 7 through 14.

The allowable bearing stress formulas included in Tables 4.5.6 (A) and (B) of the revised Specification were derived from the bearing strength formulas given in Tables (C-1) and (C-2) of this report by using a factor of safety ranging from 2.20 to 2.33. The actual factor of safety used for each case with the applicable figure and table is indicated in Tables (C-1) and (C-2).

It should be noted that the revised provisions are limited only to the thicknesses of the materials indicated in Tables 4.5.6 (A) and (B). For the thicknesses of materials not covered in these tables, the allowable bearing stress must be determined by tests. This is because the test data were not available for developing the proper design formulas.

4.5.7 Shear Stress on Bolts

In order to achieve a better coordination with the Specifications of the Research Council on Structural Connections and the American Institute of Steel Construction,[2,6] the allowable shear stresses for A325 bolts were increased by 36% in the revised design provisions. In addition, design values for A449, A490, and A354 Grade BD bolts were added for use of high strength bolts. The revised Specification permits the same allowable shear stresses for A307, A325, and A490 bolts as those specified in Refs. 12 and 13 for bearing-type connections.

It should be noted that in the revised specification, smaller allowable shear stresses are used for A449 and A354 Grade BD bolts with threads in the shear planes, as compared with those used for A325 and A490 bolts. This is based on the fact that the ratios of root area/gross area for the 1/4 in. and 3/8 in. diameter bolts are smaller than those of the 1/2 in. diameter and larger bolts. For details, see Table D. The reduced allowable shear stress for A449 and A354 Grade BD bolts are derived from the A_K/A_D ratios as follows:

For A449 bolts smaller than 1/2 in. in diameter,

$$F_v = 21 \text{ (for A325 bolts) } \frac{\text{Avg. } A_K/A_D \text{ for 1/4 in. and 3/8 in. bolts}}{\text{Avg. } A_K/A_D \text{ for 1/2 in. and 1 in. bolts}}$$

$$= 21 \times \frac{0.585}{0.670} = 18.33 \text{ ksi};$$

use $F_v = 18$ ksi.

For A354 Grade BD bolts smaller than 1/2 in. in diameter,

$$F_v = 28 \text{ (for A490 bolts) } \times \frac{0.585}{0.671} = 24.45 \text{ ksi};$$

use $F_v = 24$ ksi.

IV. SUMMARY

During the past few years, a study has been made of the structural behavior and strength of bolted connections. Based on the analyses of available test data and an additional study made of the effects of torques and washers on the strength of bolted connections, the AISI design provisions for bolted connections were revised for inclusion in the 1980 Edition of the Specification.

This final report summarizes the results of the studies and documents the background information for the revised AISI design provisions.

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TABLES AND FIGURES

Table A

Comparisons between the Revised Provisions (with Washers), the 1968 AISI Specification, and the AISC Specification

ASTM Spec.	Grade	F_u (ksi)	F_y (ksi)	$\frac{F_u}{F_y}$	Min. End Dist.			Tens. on Net Section*			Bearing Stress+		
					Revised AISI	AISI 1968 Ed.	AISC Spec.	Revised AISI	AISI 1968 Ed.	AISC Spec.	Revised AISI	AISI 1968 Ed.	AISC Spec.
A446	A	45	33	1.36	$\frac{2.00\ P}{F_u t}$	$\frac{2.27\ P}{F_u t}$	$\frac{2.00\ P}{F_u t}$	$0.60\ F_y$	$0.60\ F_y$	$0.60\ F_y$	$1.50\ F_u$	$1.54\ F_u$	$1.50\ F_u$
	B	52	37	1.41	do	$\frac{2.35\ P}{F_u t}$	do	do	do	do	do	$1.49\ F_u$	do
	C	55	40	1.38	do	$\frac{2.30\ P}{F_u t}$	do	do	do	do	do	$1.52\ F_u$	do
	D	65	50	1.30	do	$\frac{2.25\ P}{F_u t}$	do	do	$0.58\ F_y$	do	do	$1.56\ F_u$	do
A607	45	60	45	1.33	do	do	do	do	$0.59\ F_y$	do	do	$1.56\ F_u$	do
	55	70	55	1.27	do	do	do	do	$0.56\ F_y$	do	do	$1.56\ F_y$	do
	65	80	65	1.23	do	do	do	do	$0.55\ F_y$	do	do	$1.56\ F_y$	do
A611	D	52	40	1.30	do	do	do	do	$0.58\ F_y$	do	do	$1.56\ F_u$	do
A36	--	58	36	1.61	do	$\frac{2.68\ P}{F_u t}$	do	do	$0.60\ F_y$	do	do	$1.30\ F_u$	do
A588	--	70	50	1.40	do	$\frac{2.33\ P}{F_u t}$	do	do	do	do	do	$1.50\ F_u$	do
A572	65	80	65	1.23	do	$\frac{2.25\ P}{F_u t}$	do	do	$0.55\ F_y$	do	do	$1.56\ F_u$	do
A514	--	115	100	1.15	do	$\frac{2.25\ P}{F_u t}$	do	$0.50\ F_u$	$0.44\ F_u$	$0.50\ F_u$	do	$1.56\ F_u$	do

* Assume that $t \geq 3/16$ in., $r = 1$ and $d/s \geq 0.3$.

+ Assume that $t \geq 3/16$ in.

Table B

Comparisons between the Revised Provisions and the 1968 AISI Specification

ASTM Spec.	Grade	F_u (ksi)	F_y (ksi)	$\frac{F_u}{F_y}$	Allowable Tension Stress* $\frac{F_t(\text{Revised})}{F_t(\text{1968 AISI})}$		Allowable Bearing Stress $\frac{F_p(\text{Revised})}{F_p(\text{1968 AISI})}$	
					D.S.	S.S.	$F_p = 1.50F_u$	$F_p = 1.35F_u$
A446	A	45	33	1.36	1.13	1.02	0.97	0.88
	B	52	37	1.41	1.17	1.05	1.00	0.90
	C	55	40	1.38	1.15	1.03	0.98	0.88
	D	65	50	1.30	1.13	1.01	0.96	0.88
A607	45	60	45	1.33	1.13	1.01	0.96	0.87
	55	70	55	1.27	1.13	1.01	0.96	0.87
	65	80	65	1.23	1.12	1.01	0.96	0.87
A611	D	52	40	1.30	1.13	1.01	0.96	0.87
A36	-	58	36	1.61	1.34	1.21	1.15	1.04
A588	-	70	50	1.40	1.17	1.05	1.00	0.90
A572	65	80	65	1.23	1.12	1.01	0.96	0.87
A514	-	115	100	1.15	1.13	1.01	0.96	0.87

* Assume that $t < 3/16$ in., $r = 1$, $d/s = 0.1$ and 0.2.
D.S. = Double shear connection. S.S. = Single shear connection.

Table C-1

Bearing Strengths and Allowable Bearing Stresses of Bolted Connections with Washers under Both Bolt Head and Nut

<table>
<tr><th>Thickness of Steel Sheet (in.)</th><th>Type of Joint</th><th>F_u/F_y Ratio of Steel Sheet</th><th>Bearing Strength Formula</th><th>Allowable Bearing Stress, F_p (ksi)</th><th>Factor of Safety</th><th>Reference</th></tr>
<tr><td rowspan="4">< 3/16 but ≥ 0.024</td><td rowspan="2">Inside sheet of double shear connections</td><td>≥ 1.15</td><td>$\sigma_b=3.5F_u$</td><td>$1.50F_u$</td><td>2.33</td><td>Fig. 7 Table 7</td></tr>
<tr><td>< 1.15</td><td>$\sigma_b=3.0F_u$</td><td>$1.35F_u$</td><td>2.22</td><td>Fig. 8 Table 8</td></tr>
<tr><td rowspan="2">Single shear connections and outside sheets of double shear connections</td><td>≥ 1.15</td><td>$\sigma_b=3.0F_u$</td><td>$1.35F_u$</td><td>2.22</td><td>Figs. 9 & 13. Tables 9 & 13.</td></tr>
<tr><td>< 1.15</td><td>$\sigma_b=3.0F_u$</td><td>$1.35F_u$</td><td>2.22</td><td>Fig. 10 Table 10</td></tr>
</table>

Table C-2

Bearing Strengths and Allowable Bearing Stresses of Bolted Connections without Washers under Both Bolt Head and Nut

<table>
<tr><th>Thickness of Steel Sheet (in.)</th><th>Type of Joint</th><th>F_u/F_y Ratio of Steel Sheet</th><th>Bearing Strength Formula</th><th>Allowable Bearing Stress (ksi)</th><th>Factor of Safety</th><th>Reference</th></tr>
<tr><td rowspan="2">< 3/16 but ≥ 0.036</td><td>Inside sheet of double shear connections</td><td>≥ 1.15</td><td>$\sigma_b=3.0F_u$</td><td>$1.35F_u$</td><td>2.22</td><td></td></tr>
<tr><td>Single shear connections and outside sheets of double shear connections</td><td>≥ 1.15</td><td>$\sigma_b=2.2F_u$</td><td>$1.00F_u$</td><td>2.20</td><td>Figs. 11, 12 & 14. Tables 11, 12 & 14.</td></tr>
</table>

TABLE D

Gross Areas and Root Areas of Structural Bolts

Bolt Diameter (in.)	Gross Area A_D ($in.^2$)	Root Area A_K ($in.^2$)	$\frac{A_K}{A_D}$
1/4	0.049	0.027	0.55
3/8	0.110	0.068	0.62
1/2	0.196	0.126	0.64
5/8	0.307	0.202	0.66
3/4	0.442	0.302	0.68
7/8	0.601	0.419	0.70
1	0.785	0.551	0.70

Note: The gross and root areas are based on the AISC Manual of Steel Construction, 7th Edition, p. 4-125.

Table 1. Dimensions and Results of Single Shear Bolted Connections with Washers-Shear Strength Study

$F_u/F_y \geq 1.15$, $e/d < 3.5$, $t \geq 0.036$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
20A11SS	1/4	0.036	0.375	4.00	1.50	6.94	32.11	41.83	1.30	89.33	2.14	62.75	1.42	I	8
20A21SS	1/4	0.036	0.625	4.00	2.50	6.94	32.11	41.83	1.30	134.50	3.22	104.58	1.29	I	8
20A12SS	3/8	0.036	0.563	4.00	1.50	10.40	32.11	41.83	1.30	79.77	1.91	62.75	1.27	I	8
20A22SS	3/8	0.036	0.938	4.00	2.50	10.40	32.11	41.83	1.30	130.28	3.11	104.58	1.25	I	8
20A13SS	1/2	0.036	0.750	4.00	1.50	13.90	32.11	41.83	1.30	81.69	1.95	62.75	1.30	I	8
20A14SS	5/8	0.036	0.938	4.00	1.50	17.40	32.11	41.83	1.30	78.30	1.87	62.75	1.25	I	8
20A24SS	5/8	0.036	1.560	4.00	2.50	17.40	32.11	41.83	1.30	125.38	3.00	104.58	1.20	I & II	8
20A15SS	3/4	0.036	1.130	4.00	1.50	20.80	32.11	41.83	1.30	84.61	2.02	62.75	1.35	I	8
16C105SS	3/4	0.059	0.750	4.00	1.00	12.70	31.95	43.81	1.37	58.89	1.34	43.81	1.34	I	8
16C205SS	3/4	0.059	1.500	4.00	2.00	12.70	31.95	43.81	1.37	109.87	2.51	87.62	1.25	I	8
14A11SS	1/4	0.080	0.375	4.00	1.50	3.13	29.81	43.40	1.46	80.30	1.85	65.10	1.23	I	8
14A12SS	3/8	0.080	0.563	4.00	1.50	4.70	29.81	43.40	1.46	74.30	1.71	65.10	1.14	I	8
14A22SS	3/8	0.080	0.938	4.00	2.50	4.70	29.81	43.40	1.46	129.78	3.00	108.50	1.20	I	8
14A13SS	1/2	0.080	0.750	4.00	1.50	6.25	29.81	43.40	1.46	77.10	1.78	65.10	1.18	I	8
14A23SS	1/2	0.080	1.250	4.00	2.50	6.25	29.81	43.40	1.46	122.73	2.83	108.50	1.13	I	8
12A11SS	1/4	0.093	0.375	4.00	1.50	2.70	25.60	41.15	1.61	77.99	1.80	61.73	1.26	I	8
12A12SS	3/8	0.093	0.563	4.00	1.50	4.03	25.60	41.15	1.61	80.49	1.85	61.73	1.30	I	8
12A14SS	5/8	0.093	0.938	4.00	1.50	6.71	26.65	41.40	1.55	76.53	1.85	62.10	1.23	I	8
18E12SS	3/8	0.046	0.563	4.00	1.50	8.24	46.75	68.00	1.45	108.93	1.60	102.00	1.07	I	9
18E22SS	3/8	0.046	0.938	4.00	2.50	8.24	46.75	68.00	1.45	197.62	2.91	170.00	1.16	I	9
18E14SS	5/8	0.046	0.938	4.00	1.50	13.74	46.75	68.00	1.45	112.52	1.65	102.00	1.10	I	9
14E13SS	1/2	0.078	0.750	4.00	1.50	6.40	54.44	70.40	1.29	111.30	1.58	105.60	1.05	I	9
14E23SS	1/2	0.078	1.250	4.00	2.50	6.40	54.44	70.40	1.29	182.50	2.60	176.00	1.04	I	9
14E15SS	3/4	0.078	1.130	4.00	1.50	9.60	54.44	70.40	1.29	119.50	1.70	105.60	1.13	I	9

Table 1 (con't)

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
14E25SS	3/4	0.078	1.880	4.00	2.50	9.60	54.44	70.40	1.29	170.90	2.43	176.00	0.97	I & II	9
10E15SS	3/4	0.143	1.130	4.00	1.50	5.23	59.47	76.84	1.29	107.30	1.40	115.26	0.93	I	9
10E16SS	1.0	0.143	1.500	4.00	1.50	7.00	59.47	76.84	1.29	104.50	1.36	115.26	0.91	I	9
8E15SS	3/4	0.190	1.130	4.00	1.50	3.95	56.45	76.98	1.36	107.10	1.40	115.47	0.93	I	9
SS1	7/8	0.115	1.750	8.00	2.00	7.61	35.49	49.44	1.39	128.45	2.60	98.88	1.30	I	10
SS4	1.0	0.116	2.000	8.00	2.00	8.62	35.49	49.44	1.39	122.51	2.48	98.88	1.24	I	10
SS7	7/8	0.181	1.750	8.00	2.00	4.83	38.10	62.08	1.63	142.07	2.30	124.16	1.14	I	10
SS10	1.0	0.184	2.000	8.00	2.00	5.43	38.10	62.08	1.63	137.50	2.21	124.16	1.11	I	10
SS13	1.0	0.261	2.000	8.00	2.00	3.83	45.07	67.54	1.50	142.34	2.11	135.08	1.05	I	10
--	1/2	0.051	0.970	4.06	1.94	9.80	40.60	50.10	1.23	134.10	2.68	97.20	1.38	I	11
--	1/2	0.051	1.020	4.06	2.04	9.80	40.60	50.10	1.23	136.90	2.73	102.20	1.34	I	11
--	1/2	0.061	1.030	4.03	2.06	8.20	50.50	74.10	1.47	173.10	2.34	152.65	1.13	I & II	11
--	1/2	0.061	1.030	4.06	2.06	8.20	50.50	74.10	1.47	167.90	2.27	152.65	1.10	I & II	11

$*(\sigma_b)_{cal} = (e/d)\ F_u$

Mean = 1.18

Standard deviation = 0.130

The types of failure are defined as follows:

I - Longitudinal shearing of the steel sheets
II - Bearing failure between steel sheet and bolt
III - Transverse tension tearing failure
IV - Shearing of the bolt

Table 2. Dimensions and Results of Double Shear Bolted Connections with Washers-Shear Strength Study

$F_u/F_y \geq 1.15$, $e/d < 3.5$, $t \geq 0.036$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
20A11DS	1/4	0.036	0.375	4.0	1.5	6.94	32.11	41.85	1.30	95.85	2.29	62.78	1.53	I	8
20A21DS	1/4	0.036	0.625	4.0	2.5	6.94	32.11	41.85	1.30	142.75	3.41	104.63	1.36	I	8
20A12DS	3/8	0.036	0.563	4.0	1.5	10.42	32.11	41.85	1.30	93.89	2.24	62.78	1.50	I	8
20A13DS	1/2	0.036	0.750	4.0	1.5	13.90	32.11	41.85	1.30	84.42	2.02	62.78	1.34	I	8
20A14DS	5/8	0.036	0.938	4.0	1.5	17.36	32.11	41.85	1.30	88.09	2.10	62.78	1.40	I	8
20A15DS	3/4	0.036	1.125	4.0	1.5	20.83	32.11	41.85	1.30	88.70	2.12	62.78	1.41	I	8
16C103DS	1/2	0.059	0.500	4.0	1.0	8.46	31.95	43.81	1.40	58.55	1.34	43.81	1.34	I	8
16C203DS	1/2	0.059	1.000	4.0	2.0	8.46	31.95	43.81	1.40	112.69	2.57	87.62	1.29	I	8
14A11DS	1/4	0.080	0.375	4.0	1.5	3.13	29.81	43.40	1.46	78.37	1.81	65.10	1.20	I	8
14A21DS	1/4	0.080	0.625	4.0	2.5	3.13	29.81	43.40	1.46	131.86	3.04	108.50	1.22	I	8
14A12DS	3/8	0.080	0.563	4.0	1.5	4.69	29.81	43.40	1.46	83.47	1.92	65.10	1.28	I	8
14A12DS	3/8	0.080	0.938	4.0	2.5	4.69	29.81	43.40	1.46	129.33	2.98	108.50	1.19	I	8
14A13DS	1/2	0.080	0.750	4.0	1.5	6.25	29.81	43.40	1.46	81.91	1.89	65.10	1.26	I	8
14A23DS	1/2	0.080	1.250	4.0	2.5	6.25	29.81	43.40	1.46	130.58	3.01	108.50	1.20	I	8
12A11DS	1/4	0.093	0.375	4.0	1.5	2.68	26.00	41.15	1.58	82.18	2.00	61.73	1.33	I	8
12A21DS	1/4	0.093	0.625	4.0	2.5	2.68	26.00	41.15	1.58	134.81	3.28	102.88	1.31	I	8
12A12DS	3/8	0.093	0.563	4.0	1.5	4.03	26.00	41.15	1.58	79.04	1.92	61.73	1.28	I	8
12A22DS	3/8	0.093	0.938	4.0	2.5	4.03	26.00	41.15	1.58	134.39	3.27	102.88	1.31	I	8
12A14DS	5/8	0.093	0.938	4.0	1.5	6.71	26.00	41.15	1.58	83.82	2.04	61.73	1.36	I	8
12A24DS	5/8	0.093	1.563	4.0	2.5	6.71	26.00	41.15	1.58	127.73	3.10	102.88	1.24	I	8
10A12DS	3/8	0.143	0.563	4.0	1.5	2.62	36.60	48.00	1.31	84.84	1.77	72.00	1.18	I	8
10A22DS	3/8	0.143	0.938	4.0	2.5	2.62	36.60	48.00	1.31	133.56	2.78	120.00	1.11	I	8
8B23DS	1/2	0.188	1.250	4.0	2.5	2.66	35.15	47.10	1.34	124.75	2.65	117.75	1.06	I	8
8B25DS	3/4	0.188	1.880	4.0	2.5	4.00	35.15	47.10	1.34	129.16	2.74	117.75	1.10	I	8
18E12DS	3/8	0.046	0.563	4.0	1.5	8.24	46.75	68.00	1.45	110.71	1.63	102.00	1.09	I	9
18E22DS	3/8	0.046	0.938	4.0	2.5	8.24	46.75	68.00	1.45	185.37	2.73	170.00	1.09	I	9
18E14DS	5/8	0.046	0.938	4.0	1.5	13.74	46.75	68.00	1.45	110.91	1.63	102.00	1.09	I	9
18E24DS	5/8	0.046	1.563	4.0	2.5	13.74	46.75	68.00	1.45	171.97	2.53	170.00	1.01	I	9

Table 2. (con't)

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
14E13DS	1/2	0.078	0.750	4.0	1.5	6.39	54.44	70.40	1.29	122.40	1.74	105.60	1.16	I	9
14E13DS	1/2	0.078	1.250	4.0	2.5	6.39	54.44	70.40	1.29	190.90	2.71	176.00	1.08	I	9
14E15DS	3/4	0.078	1.125	4.0	1.5	9.58	54.44	70.40	1.29	121.35	1.72	105.60	1.15	I	9
10E12DS	3/8	0.143	0.563	4.0	1.5	2.61	59.50	71.85	1.21	101.55	1.41	107.78	0.94	I	9
10E13DS	1/2	0.143	0.750	4.0	1.5	3.50	59.50	71.85	1.21	107.10	1.49	107.78	0.99	I	9
10E23DS	1/2	0.143	1.250	4.0	2.5	3.50	59.50	71.85	1.21	180.80	2.52	179.63	1.01	I	9
10E15DS	3/4	0.143	1.130	4.0	1.5	5.23	59.50	71.85	1.21	121.45	1.69	107.78	1.13	I	9
10E26DS	1.0	0.143	2.500	4.0	2.5	7.00	59.50	71.85	1.21	167.00	2.32	179.63	0.93	I	9
8E15DS	3/4	0.190	1.125	4.0	1.5	3.95	56.45	76.98	1.36	108.95	1.42	115.47	0.94	I	9
8E25DS	3/4	0.190	1.875	4.0	2.5	3.95	56.45	76.98	1.36	158.30	2.06	192.45	0.82	I & II	9
16FAX-L14	1/2	0.062	1.250	2.5	2.5	8.06	30.10	45.90	1.52	101.60	2.21	114.75	0.89	I & II	12
12FAX-L19	1/2	0.106	1.250	2.5	2.5	4.72	28.10	44.10	1.57	120.20	2.73	110.25	1.09	I & II	12

$^*(\sigma_b)_{cal} = (e/d)\ F_u$

See Table 1 for the definition of type of failure

Mean = 1.18

Standard deviation = 0.168

Table 3. Dimensions and Results of Single Shear Bolted Connections with Washers-Shear Strength Study

$F_u/F_y < 1.15$, $e/d < 3.5$, $t \geq 0.036$

Spec No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
12Y-L10	5/8	0.106	2.11	4.12	3.370	5.90	72.40	72.80	1.01	204.00	2.80	245.34	0.83	I & II	12
7Y-L1	3/4	0.183	0.62	1.50	0.833	4.10	83.10	83.80	1.01	62.00	0.74	69.81	0.89	I	12
7Y-L2	3/4	0.183	0.69	1.50	0.917	4.10	83.10	83.80	1.01	64.00	0.76	76.84	0.83	I	12
7Y-T3	3/4	0.183	0.62	1.50	0.833	4.10	86.40	91.30	1.06	58.50	0.64	76.05	0.77	I	12
7Y-L4	3/4	0.183	1.00	1.88	1.330	4.10	83.10	83.80	1.01	97.20	1.16	111.45	0.87	I	12
7Y-T4	3/4	0.183	1.00	1.88	1.330	4.10	86.40	91.30	1.06	102.00	1.12	121.43	0.84	I	12
7Y-T5	3/4	0.183	1.75	3.00	2.330	4.10	86.40	91.30	1.06	186.00	2.04	212.73	0.87	I & II	12
--	1/2	0.037	1.03	4.00	2.060	13.50	53.50	58.90	1.10	159.50	2.71	121.33	1.31	I	11
--	1/2	0.037	1.06	4.03	2.200	13.50	53.50	58.90	1.10	162.70	2.76	129.58	1.26	I	11
--	1/2	0.037	1.00	4.00	2.000	13.50	53.50	58.90	1.10	149.73	2.54	117.80	1.27	I	11

* $(\sigma_b)_{cal} = (e/d)\ F_u$

Mean = 0.97

See Table 1 for the definition of type of failure.

Standard deviation = 0.214

Table 4. Dimensions and Results of Double Shear Bolted Connections with Washers-Shear Strength Study

$F_u/F_y < 1.15$, $e/d < 3.5$, $t \geq 0.036$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)_{cal}$ *	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
7Y-L22	1/2	0.183	0.88	5.00	1.75	2.73	83.10	83.80	1.01	136.8	1.63	146.65	0.93	I	12
7Y-L23	1/2	0.183	0.75	5.00	1.50	2.73	83.10	83.80	1.01	112.3	1.34	125.70	0.89	I	12
7Y-L24	1/2	0.183	1.40	5.00	2.80	2.73	83.10	83.80	1.01	263.0	3.14	234.64	1.12	I & II	12
7Y-L25	1/2	0.183	1.50	3.33	3.00	2.73	83.10	83.80	1.01	240.0	2.86	251.40	0.95	I & II	12
20Z-L5	1/2	0.038	1.00	2.50	2.00	13.16	75.70	81.70	1.08	130.8	1.60	163.40	0.80	I & II	12
20Z-L7	3/16	0.038	0.47	2.08	2.50	4.93	75.70	81.70	1.08	192.0	2.35	204.25	0.94	I	12
1605X-L5	1/2	0.062	1.00	2.50	2.00	8.06	83.25	83.25	1.00	157.0	1.89	166.50	0.94	I	12
1605X-L6	1/2	0.062	1.40	5.00	2.80	8.06	87.60	87.60	1.00	224.0	2.56	245.28	0.91	I & II	12
1205X-L10	1/2	0.106	1.40	5.00	2.80	4.72	80.50	80.50	1.00	206.0	2.56	225.40	0.91	I & II	12
7Y-L31	1/2	0.183	1.50	2.50	3.00	2.73	82.60	82.60	1.00	222.5	2.70	247.80	0.90	I	12

* $(\sigma_b)_{cal} = (e/d)\ F_u$

Mean = 0.93

See Table 1 for the definition of type of failure.

Standard deviation = 0.080

Table 5a. Dimensions and Results of Bolted Connections with Washers-Tensile Strength Study (Double Shear)

Spec. No.	d (in)	t (in)	s (in)	e/d	d/s	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{Fu}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{test}}{(\sigma_{net})_{cal}}$	Failure Type	Reference
20A21DS2	1/4	0.0347	4.0	2.5	0.063	7.2[illegible]	32.11	41.85	9.66	0.231	12.10	0.80	I & III	8
20A22DS	3/8	0.0344	4.0	2.5	0.094	10.90	32.11	41.85	14.84	0.355	16.00	0.93	I & III	8
20A23DS1	1/2	0.0354	4.0	2.5	0.125	14.12	32.11	41.85	20.80	0.497	19.90	1.05	I & III	8
20A33DS1	1/2	0.0360	4.0	3.5	0.125	13.90	32.11	41.85	23.60	0.564	19.90	1.19	III	8
20A43DS	1/2	0.0356	4.0	4.5	0.125	14.04	32.11	41.85	29.00	0.693	19.90	1.46	III	8
20A34DS	5/8	0.0354	4.0	3.5	0.156	17.66	32.11	41.85	35.81	0.856	23.77	1.51	III	8
20A44DS1	5/8	0.0360	4.0	4.5	0.156	17.36	32.11	41.85	34.56	0.826	23.77	1.45	III	8
20A25DS	3/4	0.0355	4.0	2.5	0.188	21.13	32.11	41.85	29.86	0.714	27.80	1.07	III	8
20A35DS1	3/4	0.0357	4.0	3.5	0.188	21.01	32.11	41.85	35.68	0.853	27.80	1.28	III	8
16C403DS1	1/2	0.0591	4.0	4.0	0.125	8.46	32.00	44.00	31.33	0.712	20.90	1.50	III	8
16C503DS1	1/2	0.0591	4.0	5.0	0.125	8.4[illegible]	32.00	44.00	34.98	0.795	20.90	1.67	III	8
14A43DS1	1/2	0.0770	4.0	4.5	0.125	6.49	29.80	43.40	29.77	0.686	20.62	1.44	III	8
14B25DS1	3/4	0.0797	4.0	2.5	0.188	9.41	29.80	43.40	28.38	0.654	28.82	0.98	III	8
14B35DS1	3/4	0.0770	4.0	3.5	0.188	9.74	29.80	43.40	34.27	0.790	28.82	1.19	III	8
14B26DS1	1.0	0.0760	4.0	2.5	0.250	13.23	29.80	43.40	37.60	0.866	36.90	1.02	III	8
14B36DS1	1.0	0.0734	4.0	3.5	0.250	13.62	29.80	43.40	42.39	0.977	36.90	1.15	III	8
12A34DS1	5/8	0.0922	4.0	3.5	0.156	6.78	26.00	41.15	31.83	0.774	23.37	1.36	III	8
12A44DS1	5/8	0.0922	4.0	4.5	0.156	6.78	26.00	41.15	36.87	0.896	23.37	1.58	III	8
8B35DS1	3/4	0.1970	4.0	3.5	0.188	3.81	32.00	46.00	41.40	0.900	30.54	1.36	III	8
8B45DS1	3/4	0.1808	4.0	4.5	0.188	4.15	32.00	46.00	46.50	1.010	30.54	1.52	III	8
8B45DS1	1.0	0.1910	4.0	2.5	0.250	5.24	32.00	46.00	43.35	0.942	39.10	1.11	III	8
18E34DS1	5/8	0.0451	4.0	3.5	0.156	13.86	46.75	68.00	43.98	0.647	38.62	1.14	I & III	8
18E44DS1	5/8	0.0453	4.0	4.5	0.156	13.80	46.75	68.00	45.84	0.674	38.62	1.19	I & III	9
14E25DS1	3/4	0.0781	4.0	2.5	0.188	9.60	54.44	70.40	42.10	0.598	46.75	0.90	III	9
14E45DS1	3/4	0.0781	4.0	4.5	0.188	9.54	54.44	70.40	67.40	0.957	46.75	1.44	III	9
10E25DS1	3/4	0.1351	4.0	2.5	0.188	5.55	59.50	71.85	44.85	0.624	47.71	0.94	I & III	9
10E16DS1	1.0	0.1421	4.0	1.5	0.250	7.04	59.50	71.85	35.40	0.493	61.10	0.58	I & III	9
10E46DS1	1.0	0.1411	4.0	4.5	0.250	7.09	59.50	71.85	69.40	0.966	61.10	1.14	III	9
14G25DS1	3/4	0.0768	2.0	2.5	0.375	9.77	29.80	43.40	47.80	1.100	43.40	1.10	III	9
14G35DS	3/4	0.0760	2.0	3.5	0.375	9.87	29.80	43.40	48.30	1.110	43.40	1.11	III	9
14G45DS	3/4	0.0755	2.0	4.5	0.375	9.93	29.80	43.40	49.70	1.15[illegible]	43.40	1.15	III	9

$*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u \leq F_u$

Mean = 1.20

Standard deviation = 0.251

See Table 1 for the definition of type of failure

Table 5b. Dimensions and Results of Double Shear Bolted Connections With Washers-Tensile Strength Study[12]

Spec No	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})_{cal}^*$ (ksi)	$\frac{(\sigma_{net})_{test}}{(\sigma_{net})_{cal}}$	Failure Type
20Z-L9	3/4	0.039	2.5	3.0	0.30	19.23	75.50	81.70	74.00	0.906	81.70	0.91	II & III
20ZT13	3/4	0.039	2.5	3.0	0.30	19.23	99.40	99.80	74.45	0.746	99.80	0.75	II & III
1605X-L2	3/4	0.065	2.5	3.0	0.30	11.54	83.25	83.25	85.70	1.030	83.25	1.03	III
1605XL3	3/4	0.065	2.5	2.0	0.30	11.54	83.25	83.25	68.72	0.825	83.25	0.83	I & II & III
1205X-L8	3/4	0.105	3.0	3.5	0.25	7.14	81.60	81.60	81.85	1.000	69.36	1.18	II & III
1205X-L9	7/8	0.105	3.5	3.5	0.25	8.33	81.60	81.60	83.25	1.020	69.36	1.20	II & III
1205X-L11	3/4	0.105	2.5	3.0	0.30	7.14	80.50	80.50	77.30	0.960	80.50	0.96	III
7Y-L32	5/8	0.183	3.0	3.5	0.21	3.42	82.60	82.60	66.20	0.801	60.30	1.10	I & II & III
16FAX-L12	3/4	0.060	2.5	3.0	0.30	12.50	30.10	45.90	46.00	1.000	45.90	1.00	III
16FAX-L13	3/4	0.060	2.5	3.5	0.30	12.50	30.10	45.90	46.20	1.010	45.90	1.01	III
16FAXL15	1/2	0.060	2.5	3.5	0.20	8.33	30.10	45.90	43.87	0.956	32.13	1.37	II & III
1610XL18	3/4	0.060	2.5	3.0	0.30	12.50	78.40	81.50	84.32	1.030	81.50	1.03	III
12FAXL18	3/4	0.107	2.5	3.0	0.30	7.01	28.10	44.10	45.10	1.020	44.10	1.02	III
12FAXL20	1/2	0.107	2.5	3.5	0.20	4.67	28.10	44.10	41.10	0.932	30.87	1.33	II & III
1615XL22	3/4	0.600	2.5	3.0	0.30	12.50	45.40	54.70	61.80	1.180	54.70	1.13	III
1615XL23	1/2	0.600	2.5	3.0	0.20	8.33	45.40	54.70	50.90	0.931	38.30	1.33	II & III
1625XL26	3/4	0.600	2.5	3.0	0.30	12.50	38.50	49.10	57.17	1.160	49.10	1.16	III
1625XL27	1/2	0.600	2.5	3.0	0.20	8.33	38.50	49.10	42.50	0.866	34.37	1.24	II & III
1625XL28	1/2	0.600	2.5	3.5	0.20	8.33	38.50	49.10	44.50	0.906	34.37	1.29	II & III
1210XL32	3/4	0.107	2.5	3.0	0.30	7.01	70.10	72.80	77.70	1.070	72.80	1.07	III
1210XL25	1/2	0.107	2.0	3.5	0.25	4.67	70.10	72.80	77.10	1.060	61.88	1.25	II & III
1215XL26	3/4	0.107	2.5	3.0	0.30	7.01	65.20	69.30	66.00	0.952	69.30	0.95	III
1215XL29	1/2	0.107	2.0	3.5	0.25	4.67	65.20	69.30	69.83	1.010	58.91	1.19	II & III
1225X-L30	3/4	0.107	2.5	3.0	0.30	7.01	36.60	50.00	53.61	1.070	50.00	1.07	III
1225XL31	1/2	0.107	2.5	3.0	0.20	4.67	36.60	50.00	42.40	0.848	35.00	1.21	II & III
1225XL32	1/2	0.107	2.5	3.5	0.20	4.67	36.60	50.00	42.50	0.850	35.00	1.21	II & III
1225XL33	1/2	0.107	2.0	3.5	0.25	4.67	36.60	50.00	51.50	1.030	42.50	1.23	II & III

*$(\sigma_{net})_{cal} = (.1 + 3d/s)F_u \leq F_u$

Mean = 1.11

See Table 1 for the definition of type of failure.

Standard deviation = 0.156

Table 5c. Dimensions and Results of Bolted Connections with Washers-Tensile Strength Study (Single Shear)

Spec. No.	d (in)	t (in)	s (in)	e/d	d/s	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{Fu}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{test}}{(\sigma_{net})_{cal}}$	Failure Type	Reference
20A41SS1	1/4	0.0346	4.0	4.5	0.063	7.23	32.11	41.85	15.50	0.370	12.03	1.29	III	8
20A41SS2	1/4	0.0349	4.0	4.5	0.063	7.16	32.11	41.85	14.87	0.355	12.03	1.24	III	8
20A22SS1	3/8	0.0354	4.0	2.5	0.094	10.60	32.11	41.85	13.50	0.323	16.00	0.84	I & III	8
20A32SS1	3/8	0.0335	4.0	3.5	0.094	11.20	32.11	41.85	14.74	0.352	16.00	0.92	I & III	8
20A32SS2	3/8	0.0342	4.0	3.5	0.094	10.96	32.11	41.85	19.94	0.476	16.00	1.25	III	8
20A42SS1	3/8	0.0349	4.0	4.5	0.094	10.74	32.11	41.85	14.35	0.343	16.00	0.90	I & III	8
20A42SS3	3/8	0.0360	4.0	4.5	0.094	10.42	32.11	41.85	13.10	0.313	16.00	0.82	III	8
20A23SS1	1/2	0.0352	4.0	2.5	0.125	14.20	32.11	41.85	17.15	0.410	19.90	0.86	I & III	8
20A43SS1	1/2	0.0352	4.0	4.5	0.125	14.20	32.11	41.85	17.19	0.411	19.90	0.86	I & III	8
20A43SS3	1/2	0.0361	4.0	4.5	0.125	13.90	32.11	41.85	20.55	0.491	19.90	1.03	III	8
20A34SS	5/8	0.0359	4.0	3.5	0.156	17.40	32.11	41.85	24.64	0.590	23.77	1.04	III	8
20A44SS	5/8	0.0353	4.0	4.5	0.156	17.70	32.11	41.85	21.90	0.523	23.77	0.92	III	8
20A25SS1	3/4	0.0357	4.0	2.5	0.188	21.00	32.11	41.85	25.30	0.605	27.80	0.91	III	8
20A35SS1	3/4	0.0357	4.0	3.5	0.188	21.00	32.11	41.85	25.13	0.600	27.80	0.90	III	8
16C305SS	3/4	0.0591	4.0	3.0	0.188	12.70	32.00	44.00	31.28	0.711	29.22	1.07	III	8
16C505SS	3/4	0.0591	4.0	5.0	0.188	12.70	32.00	44.00	30.32	0.690	29.22	1.04	III	8
14A23SS1	1/2	0.0832	4.0	2.5	0.125	6.00	29.80	43.40	17.97	0.414	20.62	0.87	I & III	8
14B25SS1	3/4	0.0798	4.0	2.5	0.188	9.40	29.80	43.40	25.12	0.579	28.82	0.87	III	8
14B35SS1	3/4	0.0771	4.0	3.5	0.188	9.73	29.80	43.40	23.79	0.548	28.82	0.83	III	8
14B45SS	3/4	0.0814	4.0	4.5	0.188	9.21	29.80	43.40	26.21	0.604	28.82	0.91	III	8
14B26SS1	1.0	0.0768	4.0	2.5	0.250	13.00	29.80	43.40	33.33	0.768	36.89	0.90	III	8
14B36SS1	3/4	0.0741	4.0	3.5	0.188	10.12	29.80	43.40	33.31	0.767	28.82	1.16	III	8
14B46SS1	3/4	0.0789	4.0	4.5	0.188	9.51	29.80	43.40	35.90	0.827	28.82	1.25	III	8
12A34SS1	5/8	0.0922	4.0	3.5	0.156	6.78	26.00	41.15	37.20	0.904	23.40	1.59	III	8
12A44SS1	5/8	0.0922	4.0	4.5	0.156	6.78	26.00	41.15	24.30	0.591	23.40	1.04	III	8
8B45SS1	3/4	0.1867	4.0	4.5	0.188	4.02	32.00	46.00	29.07	0.632	30.54	0.95	I & III	8
8B26SS1	1.0	0.1893	4.0	2.5	0.250	5.28	32.00	46.00	43.70	0.950	39.10	1.12	III	8
8B46SS1	1.0	0.1884	4.0	4.5	0.250	5.31	32.00	46.00	46.98	1.020	39.10	1.20	III	8
18E42SS1	3/8	0.0451	4.0	4.5	0.094	8.31	46.75	68.00	20.85	0.307	26.00	0.80	III & I	9
18E24SS1	5/8	0.0441	4.0	2.5	0.156	14.20	46.75	68.00	29.78	0.438	38.62	0.77	I & III	9
18E34SS	5/8	0.0444	4.0	3.5	0.156	14.08	46.75	68.00	37.80	0.556	38.62	0.98	III	9
18E44SS1	5/8	0.0448	4.0	4.5	0.156	13.95	46.75	68.00	35.[illegible]4	0.515	38.62	0.91	III	9
14E35SS1	3/4	0.0789	4.0	3.5	0.188	9.51	54.44	70.40	47.95	0.681	46.75	1.03	III	9
14E45SS1	3/4	0.0781	4.0	4.5	0.188	9.60	54.44	70.40	55.45	0.788	46.75	1.19	III	9
10E26SS1	1.0	0.1455	4.0	2.5	0.250	6.87	59.50	71.85	55.25	0.770	61.10	0.90	III	9
14G25SS	3/4	0.0766	2.0	2.5	0.375	9.80	29.80	43.40	49.40	1.140	43.40	1.14	III	9
14G35SS	3/4	0.0753	2.0	3.5	0.375	9.96	29.80	43.40	47.00	1.080	43.40	1.08	III	9
14G45SS	3/4	0.0795	2.0	4.5	0.375	9.43	29.80	43.40	46.50	1.070	43.40	1.07	III	9

$^*(\sigma_{net})_{cal} = (.1 + 3\ d/s)\ Fu \leq F_u$

Mean = 1.01

See Table 1 for the definition of type of failure.

Standard deviation = 0.172

Table 5d. Dimensions and Results of Single Shear Connections With Washers-Tensile Strength Study[12]

Spec No	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})_{cal}^{*}$ (ksi)	$\frac{(\sigma_{net})_{test}}{(\sigma_{net})_{cal}}$	Failure Type
12Y-L12	1/2	0.104	2.660	3.500	0.188	4.81	72.40	72.80	50.96	0.700	48.34	1.05	II & III
12Y-L13	5/8	0.104	3.330	3.480	0.188	6.01	72.40	72.80	36.00	0.495	48.34	0.74	I & II & III
12Y-L14	3/4	0.104	3.930	3.460	0.191	7.21	72.40	72.80	70.64	0.970	49.00	1.44	II & III
12Y-L15	3/8	0.104	1.520	3.990	0.247	3.61	72.40	72.80	66.12	0.910	61.22	1.08	I & II & III
12Y-L17	5/8	0.104	2.548	3.400	0.245	6.01	72.40	72.80	54.70	0.751	60.80	0.90	I & II & III
12Y-L18	3/4	0.104	3.040	3.530	0.247	7.21	72.40	72.80	52.22	0.717	61.22	0.85	II & III
12Y-L19	7/8	0.104	3.530	3.430	0.248	8.41	72.40	72.80	52.55	0.722	61.44	0.86	III
7Y-T3	3/4	0.183	1.500	0.833	0.500	4.10	86.40	91.30	84.74	0.928	91.30	0.93	III
7Y-L5	3/4	0.183	3.750	2.500	0.200	4.10	83.10	83.90	52.00	0.620	58.73	0.89	I & II & III
7Y-L6	3/4	0.183	3.750	5.000	0.200	4.10	83.10	83.10	79.00	0.951	58.73	1.35	II & III
12Y-L27	3/8	0.105	0.872	5.330	0.430	3.57	87.00	88.10	85.00	0.965	88.10	0.96	III
12Y-L28	5/8	0.105	1.500	4.000	0.420	5.95	87.00	88.10	88.70	1.010	88.10	1.01	III
7Y-T30	3/4	0.183	1.870	3.330	0.400	4.10	87.00	91.00	96.60	1.060	91.00	1.06	III
7Y-L20	3/4	0.183	1.500	1.500	0.500	4.10	83.10	83.80	84.60	1.010	83.80	1.01	III
7Y-L21	3/4	0.183	2.500	3.200	0.300	4.10	83.10	83.80	83.10	0.992	83.80	0.99	III
20Z-L1	1/2	0.039	1.500	3.500	0.330	12.82	75.50	81.70	85.30	1.040	81.70	1.04	III
20Z-L2	1/2	0.039	1.500	2.000	0.330	12.82	75.50	81.70	74.90	0.917	81.70	0.92	I & II & III
20Z-L3	3/4	0.039	2.500	2.000	0.300	19.23	75.50	81.70	63.80	0.781	81.70	0.78	I & II & III
20Z-T10	1/2	0.039	1.500	3.500	0.330	12.82	94.40	99.80	70.80	0.710	99.80	0.71	III
20Z-T11	1/2	0.039	2.500	3.000	0.200	12.82	94.40	99.80	40.23	0.403	70.00	0.57	II & III
1605X-L1	3/4	0.065	2.500	3.000	0.300	11.54	83.25	83.25	81.30	0.977	83.25	0.98	III
16FAX-L16	1/2	0.060	2.500	3.500	0.200	8.33	30.10	45.90	41.30	0.900	32.13	1.29	II & III

$^{*}(\sigma_{net})_{cal} = (.1 + 3d/s)F_u \le F_u$

See Table 1 for the definition of type of failure.

Mean = 0.97

Standard deviation = 0.203

Table 5e. Dimensions and Results of Multi-Bolted Connections With Washers-Tensile Strength Study[13] (Single Shear)

Spec No	No of Bolts	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})_{cal}^*$ (ksi)	$\frac{(\sigma_{net})_{test}}{(\sigma_{net})_{cal}}$	Failure Type
4F16A	1	3/4	0.060	4.01	4.00	0.1875	12.50	31.00	44.40	23.40	0.527	29.42	0.80	II & III
8F351	1	1 1/8	0.185	4.00	2.67	0.2810	6.08	55.70	77.40	68.70	0.887	73.00	0.94	II & III
14F451	1	1/2	0.078	4.00	6.00	0.1250	6.41	62.50	76.20	28.40	0.373	36.20	0.78	II & III
16A15	1	1/2	0.060	4.00	6.00	0.1250	8.33	31.60	45.00	20.00	0.445	21.40	0.93	III
3C16A	2	1/2	0.060	4.00	3.50	0.1250	8.33	31.00	44.40	37.60	0.847	32.75	1.15	II & III
4C16A	2	3/4	0.058	4.01	2.33	0.1875	12.93	31.00	44.40	40.00	0.903	36.91	1.08	II & III
8F352	2	1 1/8	0.185	4.00	2.67	0.2810	6.08	55.70	77.40	80.40	1.040	75.20	1.07	II & III
10F452	2	3/4	0.144	4.00	3.33	0.1875	5.21	62.80	80.70	74.60	0.926	67.10	1.11	III
14F452	2	1/2	0.078	4.00	5.00	0.1250	6.41	62.50	76.20	64.00	0.841	56.20	1.14	II & III
316A1	3	1/2	0.060	4.00	3.50	0.1250	8.33	31.60	45.00	37.80	0.840	37.13	1.02	III
316A2	3	1/2	0.060	4.00	3.50	0.1250	8.33	31.60	45.00	42.00	0.933	37.13	1.13	III
116A3	3	3/4	0.060	4.00	2.33	0.1875	12.50	31.60	45.00	43.50	0.968	39.94	1.09	III
216A3	3	3/4	0.060	4.00	2.33	0.1875	12.50	31.60	45.00	43.00	0.956	39.94	1.08	III
16051A	3	1/2	0.060	4.00	4.00	0.1250	8.33	84.90	84.90	85.00	1.000	70.04	1.21	III
16052A	3	3/4	0.060	4.00	2.33	0.1875	12.50	84.90	84.90	100.00	1.180	75.35	1.33	III
16101A	3	1/2	0.060	4.00	4.00	0.1250	8.33	75.60	79.30	81.00	1.020	65.42	1.24	III
16102A	3	3/4	0.060	4.00	2.33	0.1875	12.50	75.60	79.30	86.40	1.090	70.40	1.23	III
7085S	3	5/8	0.184	3.22	5.00	0.1940	3.40	85.00	85.00	86.40	1.020	76.00	1.14	III
7091S	3	5/8	0.182	3.30	5.00	0.1940	3.40	86.25	86.25	84.80	0.983	76.76	1.10	III
7092S	3	5/8	0.183	4.23	6.80	0.1480	3.40	86.25	86.25	84.75	0.983	73.14	1.16	III
7093S	3	5/8	0.185	4.23	6.80	0.1480	3.40	86.25	86.25	83.60	0.970	73.14	1.14	III

*$(\sigma_{net})_{cal} = (1 - .9r + 3rd/s)F_u \leq F_u$

See Table 1 for the definition of type of failure.

Mean = 1.09

Standard deviation = 0.135

Table 6. Dimensions and Results of Single Shear Bolted Connections without Washers - Tensile Strength Study[11]

Test No.	No. of Bolts	d (in.)	t (in.)	s (in.)	e/d	d/s	d/t	F_y (in.)	F_u (in.)	$(\sigma_{net})_t$ (ksi)	$\frac{(\sigma_{net})_t}{F_u}$	$(\sigma_{net})_c^*$ (ksi)	$\frac{(\sigma_{net})_t}{(\sigma_{net})_c}$**	Failure Type
35	1	1/2	0.037	1.51	2.06	0.331	13.51	53.5	58.9	58.00	0.985	48.74	1.19	III
36	1	1/2	0.037	1.53	2.00	0.327	13.51	53.5	58.9	57.68	0.979	48.15	1.20	III
37	2	1/2	0.037	1.00	2.00	0.500	13.51	53.5	58.9	105.02	1.783	58.90	1.78	III
38	2	1/2	0.037	1.00	2.00	0.500	13.51	53.5	58.9	93.28	1.584	58.90	1.58	III
39	3	1/2	0.037	1.00	2.00	0.500	13.51	53.5	58.9	108.73	1.846	58.90	1.85	III
40	3	1/2	0.037	1.00	2.00	0.500	13.51	53.5	58.9	66.10	1.122	58.90	1.12	III
41	2	1/2	0.037	2.00	2.00	0.250	13.51	53.5	58.9	62.80	1.066	47.86	1.31	III
42	2	1/2	0.037	2.00	2.00	0.250	13.51	53.5	58.9	67.12	1.140	47.86	1.40	III
43	3	1/2	0.037	2.00	2.00	0.250	13.51	53.5	58.9	66.37	1.127	51.54	1.29	III
44	3	1/2	0.037	2.00	2.00	0.250	13.51	53.5	58.9	64.11	1.088	51.54	1.24	III
57	2	1/2	0.061	2.00	2.00	0.250	8.20	50.5	74.1	78.80	1.063	60.21	1.31	III
58	2	1/2	0.061	2.00	2.00	0.250	8.20	50.5	74.1	81.77	1.104	60.21	1.36	III
59	3	1/2	0.061	1.00	2.00	0.500	8.20	50.5	74.1	109.41	1.477	74.10	1.48	III
60	3	1/2	0.061	1.00	2.00	0.500	8.20	50.5	74.1	113.54	1.532	74.10	1.53	III
61	1	1/2	0.061	1.01	4.00	0.495	8.20	50.5	74.1	111.00	1.498	74.10	1.50	III
62	1	1/2	0.061	1.01	4.00	0.495	8.20	50.5	74.1	106.60	1.439	74.10	1.44	III
63	1	1/2	0.061	1.01	4.00	0.495	8.20	50.0	74.1	97.81	1.320	74.10	1.32	III

* $(\sigma_{net})_c = (1 - r + 2.5rd/s)\ F_u \leq F_u$

** Except for two tests, the test data plotted in Fig. 6 for $\sigma_{net}/F_u < 1.0$ are not given in Ref. 11. For this reason, the mean value of $(\sigma_{net})_t/(\sigma_{net})_c$ is not included.

Table 7. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Double Shear)

$F_u/F_y \geq 1.15$, $e/d \geq 3.5$, $t \geq 0.036$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
20A41DS	1/4	0.0360	1.125	4.0	4.5	6.94	32.11	41.85	1.30	206.32	4.93	146.48	1.41	II	8
16C403DS	1/2	0.0591	2.000	4.0	4.0	8.46	31.95	43.95	1.38	224.03	5.10	153.83	1.46	II	8
16C503DS	1/2	0.0591	2.500	4.0	5.0	8.46	31.95	43.95	1.38	243.66	5.54	153.83	1.58	II	8
14E35DS	3/4	0.0783	2.625	4.0	3.5	9.58	54.44	70.40	1.29	242.20	3.44	246.40	0.98	I & II	9
10E36DS	1.0	0.1430	3.500	4.0	3.5	6.98	59.50	71.85	1.21	199.35	2.77	251.48	0.79	II	9
10E46DS	1.0	0.1430	4.500	4.0	4.5	6.98	59.50	71.85	1.21	201.50	2.80	251.48	0.80	II	9
16FAXL15	1/2	0.0620	1.750	2.5	3.5	8.06	30.10	45.90	1.52	161.80	3.53	160.65	1.01	II & III	12
16FAXL17	1/2	0.0620	1.750	5.0	3.5	8.06	30.10	45.90	1.52	136.00	2.96	160.65	0.85	II	12
12FAX-L20	1/2	0.1060	1.750	2.5	3.5	4.72	28.10	44.10	1.57	159.20	3.61	154.35	1.03	II & III	12
12FAX-L21	1/2	0.1060	1.750	5.0	3.5	4.72	28.10	44.10	1.57	178.40	4.05	154.35	1.16	II	12
DS1-1	7/8	0.1160	3.060	8.0	3.5	7.54	35.49	49.44	1.39	161.58	3.27	173.04	0.93	II	10
DS1-2	7/8	0.1160	3.060	8.0	3.5	7.54	35.49	49.44	1.39	148.77	3.01	173.04	0.86	II	10
DS2-1	1.0	0.1150	3.500	8.0	3.5	8.70	35.49	49.44	1.39	139.13	2.81	173.04	0.80	II	10
DS2-2	1.0	0.1160	3.500	8.0	3.5	8.62	35.49	49.44	1.39	143.10	2.90	173.04	0.83	II	10
DS3-1	7/8	0.1810	3.060	8.0	3.5	4.83	38.10	62.08	1.63	209.94	3.38	217.28	0.97	II	10
DS3-2	7/8	0.1800	3.060	8.0	3.5	4.86	38.10	62.08	1.63	196.14	3.16	217.28	0.90	II	10
DS4-1	1.0	0.1820	3.500	8.0	3.5	5.49	38.10	62.08	1.63	229.12	3.69	217.28	1.05	II	10
DS4-2	1.0	0.1810	3.500	8.0	3.5	5.52	38.10	62.08	1.63	223.76	3.60	217.28	1.03	II	10
DS5-1	1.0	0.2590	3.500	8.0	3.5	3.86	45.07	67.54	1.50	221.62	3.28	236.39	0.94	II	10
DS5-2	1.0	0.2600	3.500	8.0	3.5	3.85	45.07	67.54	1.50	222.31	3.29	236.39	0.94	II	10

Mean = 1.02

Standard deviation = 0.225

$^*(\sigma_b)_{cal} = 3.5\,F_u$

See Table 1 for definition of type of failure.

Table 8. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Double Shear)

$F_u/F_y < 1.15$, $e/d \geq 3.5$, $t \geq 0.036$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
20Z-L8	3/16	0.038	0.66	2.08	3.52	4.93	75.7	81.7	1.08	206.0	2.52	245.1	0.84	II & I	12
1205XL7	3/4	0.106	2.63	3.75	3.50	7.08	81.6	81.6	1.00	252.0	3.09	244.8	1.03	II & I	12
1205XL8	3/4	0.106	2.63	3.00	3.50	7.08	81.6	81.6	1.00	236.0	2.90	244.8	0.96	II & III	12
1205XL9	7/8	0.106	3.06	3.50	3.50	8.25	81.6	81.6	1.00	242.0	3.00	244.8	0.99	II & III	12
7Y-L32	5/8	0.183	2.19	2.98	3.50	3.42	82.6	82.6	1.00	247.0	3.03	247.8	1.00	II & I	12

*$(\sigma_b)_{cal} = 3.0\ F_u$

Mean = 0.96

See Table 1 for definition of type of failure.

Standard deviation = 0.074

Table 9. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Single Shear)

$F_u/F_y \geq 1.15$, $e/d \geq 3.5$, $t \geq 0.36$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
20A41SS	1/4	0.036	1.125	4.00	4.50	6.94	32.11	41.83	1.30	208.29	4.98	125.49	1.66	II	8
14A43SS	1/2	0.080	2.250	4.00	4.50	6.25	29.81	43.40	1.46	177.50	4.09	130.20	1.36	II	8
10E36SS	1.0	0.143	3.500	4.00	3.50	6.98	59.47	76.84	1.29	172.25	2.24	230.52	0.75	II	9
16FAX-L16	1/2	0.062	1.750	2.50	3.50	8.06	30.10	45.90	1.52	152.20	3.32	137.70	1.01	II & III	12
SS2	7/8	0.116	3.060	8.00	3.50	7.54	35.49	49.44	1.39	158.57	3.21	148.32	1.07	II	10
SS2-1	7/8	0.116	3.060	8.00	3.50	7.54	35.49	49.44	1.39	121.92	2.47	148.32	0.82	II	10
SS3	7/8	0.116	4.400	8.00	5.00	7.54	35.49	49.44	1.39	149.29	3.02	148.32	1.01	II	10
SS5	1.0	0.116	3.500	8.00	3.50	8.62	35.49	49.44	1.39	133.84	2.71	148.32	0.90	II	10
SS5-1	1.0	0.116	3.500	8.00	3.50	8.70	35.49	49.44	1.39	117.61	2.38	148.32	0.79	II	10
SS6	1.0	0.116	3.500	8.00	5.00	8.62	35.49	49.44	1.39	132.25	2.70	148.32	0.89	II	10
SS8	7/8	0.181	3.060	8.00	3.50	4.83	38.10	62.08	1.63	208.37	3.36	186.24	1.12	II	10
SS8-1	7/8	0.181	3.060	8.00	3.50	4.83	38.10	62.08	1.63	156.59	2.52	186.24	0.84	II	10
SS9	7/8	0.185	4.375	8.00	5.00	4.73	38.10	62.08	1.63	202.32	3.26	186.24	1.09	II	10
SS11	1.0	0.184	3.500	8.00	3.50	5.43	38.10	62.08	1.63	200.00	3.22	186.24	1.07	II	10
SS11-1	1.0	0.184	3.500	8.00	3.50	5.43	38.10	62.08	1.63	164.67	2.65	186.24	0.88	II	10
SS12	1.0	0.184	5.000	8.00	5.00	5.43	38.10	62.08	1.63	191.85	3.09	186.24	1.03	II	10
SS14	1.0	0.261	3.500	8.00	3.50	3.83	45.07	67.54	1.50	216.86	3.21	202.62	1.07	II	10
SS14-1	1.0	0.259	3.500	8.00	3.50	3.86	45.07	67.54	1.50	178.96	2.65	202.62	0.88	II	10
SS15	1.0	0.255	5.000	8.00	5.00	3.92	45.07	67.54	1.50	217.65	3.22	202.62	1.07	II	10
--	1/2	0.051	2.030	4.00	4.06	9.80	40.60	50.10	1.23	158.80	3.17	150.30	1.06	II & I	11
--	1/2	0.051	2.030	4.00	4.06	9.80	40.60	50.10	1.23	165.90	3.31	150.30	1.10	II & I	11
--**	1/2	0.061	1.940	2.03	3.88	8.20	50.50	74.10	1.47	201.70	2.72	222.30	0.91	II	11

$^*(\sigma_b)_{cal} = 3.0\ F_u$

Mean = 1.02

**Two bolts perpendicular to line of stress

Standard deviation = 0.200

See Table 1 for the definition of type of failure

Table 10. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Single Shear)

$F_u/F_y < 1.15$, $e/d \geq 3.5$, $t \geq 0.036$

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type	Ref. No.
12Y-L7	1/2	0.106	1.75	4.00	3.50	4.72	72.40	72.80	1.01	239.0	3.28	218.40	1.09	II & I	12
12Y-L8	3/8	0.106	1.50	2.53	4.00	3.54	72.40	72.80	1.01	245.0	3.36	218.40	1.12	II	12
12Y-L9	1/2	0.106	1.75	3.41	3.50	4.72	72.40	72.80	1.01	267.0	3.37	218.40	1.22	II	12
12Y-L11	3/8	0.106	1.49	2.00	4.00	3.54	72.40	72.80	1.01	216.0	2.97	218.40	0.99	II & I	12
12Y-L12	1/2	0.106	1.75	2.66	3.50	4.72	72.40	72.80	1.01	211.0	2.90	218.40	0.96	II & III	12
12Y-L15	3/8	0.106	1.50	1.52	4.00	3.54	72.40	72.80	1.01	194.0	2.66	218.40	0.89	II & III	12
12Y-L16	1/2	0.106	1.75	2.04	3.50	4.72	72.40	72.80	1.01	211.0	2.90	218.40	0.96	II	12
12Y-L18	3/4	0.106	2.65	3.04	3.53	7.08	72.40	72.80	1.01	153.0	2.10	218.40	0.70	II	12
7Y-L6	3/4	0.183	3.75	3.75	5.00	4.10	83.10	83.80	1.01	307.0	3.66	251.40	1.22	II & III	12
20ZT12	3/16	0.038	0.66	2.08	3.50	4.93	99.40	99.80	1.00	260.0	2.61	299.40	0.87	II	12
--	1/2	0.037	2.00	4.00	4.00	13.50	53.50	58.90	1.10	200.0	3.40	176.70	1.13	II	11
--	1/2	0.037	2.00	4.03	4.00	13.50	53.50	58.90	1.10	197.8	3.36	176.70	1.12	II	11
--	5/16	0.037	2.06	4.06	6.60	8.45	53.50	58.90	1.10	183.4	3.11	176.70	1.04	II	11
--	5/16	0.037	2.04	4.06	6.53	8.45	53.50	58.90	1.10	190.4	3.23	176.70	1.08	II	11
--	1/2	0.037	2.50	4.00	5.00	13.50	53.50	58.90	1.10	207.6	3.52	176.70	1.17	II	11
--	1/2	0.037	2.00	4.00	4.00	13.50	53.50	58.90	1.10	214.6	3.64	176.70	1.21	II & I	11

$*(\sigma_b)_{cal} = 3.0\ F_u$

Mean = 1.05

**Two bolts perpendicular to line of stress

Standard deviation = 0.145

See Table I for the definition of type of failure

Table 11. Dimensions and Results of Bolted Connections without Washers-Bearing and Shear Strength[11]

$F_u/F_y \geq 1.5$, $t \geq 0.036$

Gage of Steel	Connection* Type	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)_{cal}$** (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type
17	1	1/2	0.051	2.06	4.03	4.12	9.80	40.6	50.1	1.23	113.30	2.26	110.22	1.03	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.80	40.6	50.1	1.23	117.00	2.34	110.22	1.06	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.80	40.6	50.1	1.23	115.30	2.30	110.22	1.05	I & II
17	3	5/16	0.051	2.05	1.35	6.56	6.13	40.6	50.1	1.23	109.60	2.19	110.22	0.99	II
17	3	5/16	0.051	2.07	1.35	6.62	6.13	40.6	50.1	1.23	112.70	2.25	110.22	1.02	II
17	2	1/2	0.051	1.97	2.02	3.94	9.80	40.6	50.1	1.23	109.20	2.18	110.22	0.99	I & II
16	2	1/2	0.061	1.97	2.00	3.94	8.20	50.5	74.1	1.47	147.20	2.00	163.02	0.90	II
14	1	3/4	0.079	3.00	4.00	4.00	9.50	52.8	65.9	1.25	145.10	2.20	144.98	1.00	I & II
14	1	3/4	0.079	3.01	4.00	4.00	9.50	52.8	65.9	1.25	137.60	2.09	144.98	0.95	I & II
14	1	3/4	0.079	3.00	4.00	4.00	9.50	52.8	65.9	1.25	154.80	2.35	144.98	1.07	I & II
12	1	3/4	0.104	3.03	4.06	4.04	7.20	59.3	70.6	1.19	160.30	2.27	155.32	1.11	I & II
16	1	1/2	0.061	0.51	4.00	1.02	8.20	50.5	74.1	1.48	90.82	1.23	75.58	1.20	I & II
16	1	1/2	0.061	0.52	4.00	1.04	8.20	50.1	74.1	1.48	101.30	1.37	77.06	1.31	I & II
16	3	1/2	0.061	1.00	4.03	2.00	8.20	50.1	74.1	1.48	143.20	1.93	148.20	0.97	I & II
16	3	1/2	0.061	1.00	4.06	2.00	8.20	50.1	74.1	1.48	147.50	2.00	148.20	1.00	I & II
17	1	1/2	0.051	1.50	2.02	3.00	9.80	40.6	50.1	1.23	112.20	2.24	110.22	1.02	I
17	1	1/2	0.051	1.44	2.02	2.88	9.80	40.6	50.1	1.23	113.70	2.27	110.22	1.03	I

All single shear connections

* 1 One Bolt
2 Two bolts parallel to the line of stress
3 Three bolts parallel to the line of stress

** For $e/d \leq 2.2$, $(\sigma_b)_{cal} = (e/d)\, F_u$

For $e/d > 2.2$, $(\sigma_b)_{cal} = 2.2\, F_u$

For $e/d \leq 2.2$:
Mean = 1.12
Standard deviation = 0.163

For $e/d > 2.2$:
Mean = 1.02
Standard deviation = 0.059

Table 12a. Dimensions and Results of Bolted Connections Without Washers-Shear Strength Study[11]

$F_u/F_y < 1.15$, $t \geq 0.036$ in.

Gage of Steel	Connection* Type	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)_{cal}^{**}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type
20	1	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	1.10	129.20	2.19	117.80	1.10	I & II
20	1	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	1.10	127.70	2.17	117.80	1.08	I & II
20	1	1/2	0.037	0.50	4.00	1.00	13.5	53.5	58.9	1.10	90.81	1.54	53.50	1.70	I
20	1	1/2	0.037	0.50	4.00	1.00	13.5	53.5	58.9	1.10	82.20	1.40	53.50	1.54	I
20	3	1/2	0.037	1.00	3.94	2.00	13.5	53.5	58.9	1.10	116.60	2.00	117.80	0.99	I
20	3	1/2	0.037	1.00	3.94	2.00	13.5	53.5	58.9	1.10	116.76	2.00	117.80	0.99	I
20	2	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	1.10	118.40	2.01	117.80	1.01	I
20	2	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	1.10	116.80	2.00	117.80	0.99	I

All Single Shear Connections

Mean = 1.18

Standard deviation = 0.281

* 1 One Bolt
  2 Two bolts parallel to the line of stress
  3 Three bolts parallel to the line of stress

** $(\sigma_b)_{cal} = (e/d)F_u$

See Table 1 for the definition of type of failure.

Table 12b. Dimensions and Results of Single Shear Bolted Connections without Washers-Bearing Strength Study[11]

$F_u/F_y < 1.15$, $t \geq 0.036$ in.

Gage of Steel	Connection* Type	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)_{cal}^{**}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type
20	1	1/2	0.037	2.06	4.06	4.06	13.50	53.5	58.9	1.10	133.0	2.26	129.58	1.03	I & II
20	1	5/16	0.037	2.04	4.03	6.53	8.45	53.5	58.9	1.10	158.4	2.70	129.58	1.22	II
20	1	5/16	0.037	2.06	4.12	6.60	8.45	53.5	58.9	1.10	138.4	2.35	129.58	1.07	I & II
20	1	1/2	0.037	2.50	4.00	5.00	13.50	53.5	58.9	1.10	122.2	2.07	129.58	0.94	II
20	1	1/2	0.037	2.50	4.00	5.00	13.50	53.5	58.9	1.10	125.0	2.12	129.58	0.96	II
20	1	1/2	0.037	1.50	4.00	3.00	13.50	53.5	58.9	1.10	130.3	2.21	129.58	1.01	I
20	1	1/2	0.037	1.50	3.06	3.00	13.50	53.5	58.9	1.10	123.8	2.10	129.58	0.96	I
20	1	1/2	0.037	1.50	3.03	3.00	13.50	53.5	58.9	1.10	122.2	2.07	129.58	0.94	I
20	1	1/2	0.037	2.03	4.06	4.06	13.50	53.5	58.9	1.10	120.5	2.05	129.58	0.93	I
20	1	1/2	0.037	2.07	4.06	4.14	13.50	53.5	58.9	1.10	131.4	2.23	129.58	1.01	I
20	1	1/2	0.037	1.50	4.00	3.00	13.50	53.5	58.9	1.10	134.1	2.28	129.58	1.03	I
20	1	1/2	0.037	1.75	4.00	3.50	13.50	53.5	58.9	1.10	121.6	2.06	129.58	0.94	I
20	1	1/2	0.037	2.00	4.00	4.00	13.50	53.5	58.9	1.10	138.9	2.36	129.58	1.07	I

* 1 - One Bolt

** $(\sigma_b)_{cal} = 2.2\ F_u$

See Table 1 for the definition of type of failure.

Mean = 1.01

Standard deviation = 0.081

Table 13. Dimensions and Results of Single Shear Bolted Connections with Washers - Shear and Bearing Strength Study

$F_u/F_y \geq 1.15$, $t \leq 0.036$ in.

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type
B-1-1-1-0	1/4	0.0270	0.375	0.99	1.50	9.26	44.06	53.25	1.21	82.96	1.56	79.88	1.04	I
B-1-1-2-0	1/4	0.0275	0.375	0.99	1.50	9.09	44.06	53.25	1.21	74.91	1.41	79.88	0.94	I
B-1-1-3-T	1/4	0.0270	0.375	0.99	1.50	9.26	44.06	53.25	1.21	86.81	1.63	79.88	1.09	I
B-1-1-4-T	1/4	0.0280	0.375	0.99	1.50	8.93	44.06	53.25	1.21	85.00	1.60	79.88	1.06	I
B-1-2-1-0	3/8	0.0270	0.953	3.16	2.54	13.89	44.06	53.25	1.21	135.30	2.54	135.26	1.00	I
B-1-2-2-0	3/8	0.0265	0.923	3.19	2.46	14.15	44.06	53.25	1.21	127.30	2.39	131.00	0.97	I
B-1-2-3-T	3/8	0.0265	0.938	3.17	2.50	14.15	44.06	53.25	1.21	127.10	2.39	133.13	0.95	I
B-1-2-4-T	3/8	0.0265	0.938	3.17	2.50	14.15	44.06	53.25	1.21	127.30	2.39	133.13	0.96	I
B-1-8-1-T	3/8	0.0250	1.313	5.22	3.50	15.00	45.00	52.00	1.56	146.13	2.81	156.00	0.94	II
B-1-3-3-T	3/8	0.0250	1.313	5.23	3.50	15.00	45.00	52.00	1.56	130.13	2.50	156.00	0.83	II
B-1-9-1-T	3/8	0.0240	1.658	5.22	4.42	15.63	45.00	52.00	1.56	160.00	3.08	156.00	1.03	II
B-1-9-2-T	3/8	0.0240	1.688	5.22	4.50	15.63	45.00	52.00	1.56	137.56	2.65	156.00	0.88	II
B-1-9-3-T	3/8	0.0240	1.688	5.22	4.50	15.63	45.00	52.00	1.56	190.22	3.66	156.00	1.22	II

*$(\sigma_b)_{cal} = (e/d)\ F_u$ for $e/d \leq 3.0$

$(\sigma_b)_{cal} = 3.0\ F_u$ for $e/d > 3.0$

See Table 1 for the definition of type of failure.

All tests were conducted at the University of Missouri-Rolla in 1976.

For $e/d \leq 3.0$:
Mean = 1.00
Standard deviation = 0.056

For $e/d > 3.0$:
Mean = 0.98
Standard deviation = 0.153

Table 14. Dimensions and Results of Double Shear Bolted Connections without Washers - Bearing Strength Study

$F_u/F_y \geq 1.15$, $t \geq 0.036$ in.

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure Type
B-0-5-1-T	1/2	0.046	1.72	6.875	3.44	10.87	43.83	55.73	1.27	110.35	1.98	122.61	0.90	II
B-0-5-2-T	1/2	0.046	1.72	6.875	3.44	10.87	43.83	55.73	1.27	115.00	2.06	122.61	0.94	II
B-0-5-3-T	1/2	0.046	1.75	6.750	3.50	10.87	43.83	55.73	1.27	114.26	2.05	122.61	0.93	II
B-0-5-4-T	1/2	0.047	1.75	6.840	3.50	10.64	43.83	55.73	1.27	122.04	2.19	122.61	1.00	II
B-0-5-5-T	1/2	0.047	1.75	6.840	3.50	10.64	43.83	55.73	1.27	120.43	2.16	112.61	0.98	II
B-0-6-1-T	1/2	0.046	2.25	6.750	4.50	10.87	43.83	55.73	1.27	116.30	2.09	122.61	0.95	II
B-0-6-2-T	1/2	0.046	2.25	6.720	4.50	10.87	43.83	55.73	1.27	104.57	1.88	122.61	0.85	II
B-0-6-3-T	1/2	0.046	2.25	6.750	4.50	10.87	43.83	55.73	1.27	107.40	1.93	122.61	0.88	II

$^*(\sigma_b)_{cal} = 2.2\ F_u$ for $e/d \geq 2.2$

Mean = 0.93

Standard deviation = 0.050

See Table 1 for the definition of type of failure.

All tests were conducted at the University of Missouri-Rolla in 1976.

Table 15. Dimensions and Results of Single Shear Bolted Connections without Washers - Shear and Bearing Strength Study

$F_u/F_y \geq 1.15$, $t \leq 0.036$ in.

Spec. No.	d (in.)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	$\frac{F_u}{F_y}$	$(\sigma_b)_{test}$	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure** Type
B-0-1-1-0	1/4	0.027	0.375	0.99	1.50	9.26	44.06	53.25	1.21	77.00	1.45	79.88	0.96	I
B-0-1-2-0	1/4	0.027	0.375	1.00	1.50	9.26	44.06	53.25	1.21	82.96	1.56	79.88	1.04	I
B-0-1-3-T	1/4	0.026	0.375	1.00	1.50	9.62	44.06	53.25	1.21	78.92	1.48	79.88	0.99	I
B-0-1-4-T	1/4	0.026	0.375	1.00	1.50	9.62	44.06	53.25	1.21	78.92	1.48	79.88	0.99	I
B-0-2-1-0	3/8	0.027	0.923	3.17	2.46	13.89	44.06	53.25	1.21	79.70	1.50	117.15	0.68	
B-0-2-2-0	3/8	0.027	0.938	3.17	2.50	13.89	44.06	53.25	1.21	75.16	1.41	117.15	0.64	
B-0-2-3-T	3/8	0.027	0.953	3.17	2.54	13.89	44.06	53.25	1.21	80.50	1.54	117.15	0.69	
B-0-2-4-T	3/8	0.027	0.93[illegible]	3.16	2.50	13.89	44.06	53.25	1.21	79.21	1.49	117.15	0.68	
B-0-3-1-0	3/8	0.027	1.313	3.17	3.50	13.89	44.06	53.25	1.21	76.84	1.44	117.15	0.66	
B-0-3-2-0	3/8	0.027	1.313	3.16	3.50	13.89	44.06	53.25	1.21	81.48	1.53	117.15	0.70	
B-0-3-3-T	3/8	0.027	1.313	3.17	3.50	13.89	44.06	53.25	1.21	86.12	1.62	117.15	0.74	
B-0-3-4-T	3/8	0.027	1.313	3.17	3.50	13.89	44.06	53.25	1.21	87.01	1.63	117.15	0.74	
B-0-3-7-T	3/8	0.026	1.313	3.22	3.50	14.42	45.03	52.03	1.16	85.44	1.64	114.47	0.75	
B-0-3-8-T	3/8	0.026	1.300	3.23	3.46	14.42	45.03	52.03	1.16	80.62	1.58	114.47	0.70	
B-0-4-1-0	3/8	0.026	1.688	3.16	4.50	14.42	44.06	53.25	1.21	77.64	1.46	117.15	0.66	
B-0-4-2-0	3/8	0.026	1.703	3.19	4.54	14.42	44.06	53.25	1.21	76.41	1.43	117.15	0.65	
B-0-4-3-T	3/8	0.027	1.688	3.17	4.50	13.89	44.06	53.25	1.21	79.01	1.48	117.15	0.67	
B-0-4-4-T	3/8	0.027	1.688	3.17	4.50	13.89	44.06	53.25	1.21	82.96	1.56	117.15	0.71	

*$(\sigma_b)_{cal} = 2.2\ F_u$ for $e/d \geq 2.2$, $(\sigma_b)_{cal} = (e/d)\ F_u$ for $e/d < 2.2$

See Table 1 for the definition of type of failure

For $e/d < 2.2$:
Mean = 1.00
Standard deviation = 0.034

All tests were conducted at the University of Missouri-Rolla in 1976.

** When $e/d > 2.2$, the connections did not fail for the type of bearing defined by the AISI Specification. Therefore, the formula for bearing strength is not applicable.

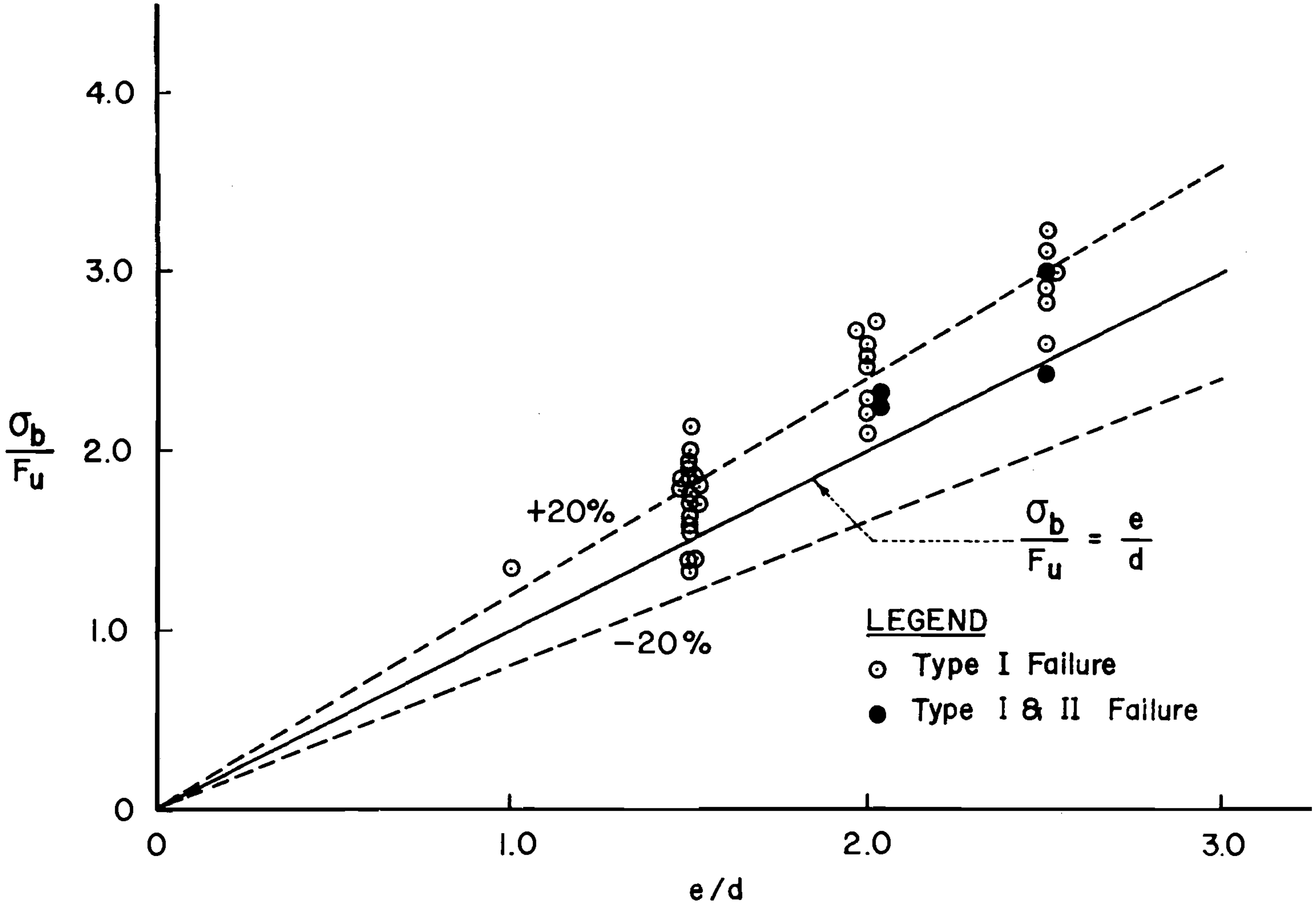

Fig. 1 Single Shear Connections with Washers, $F_u/F_y \geq 1.15$, $e/d < 3.5$, Shear Strength Study

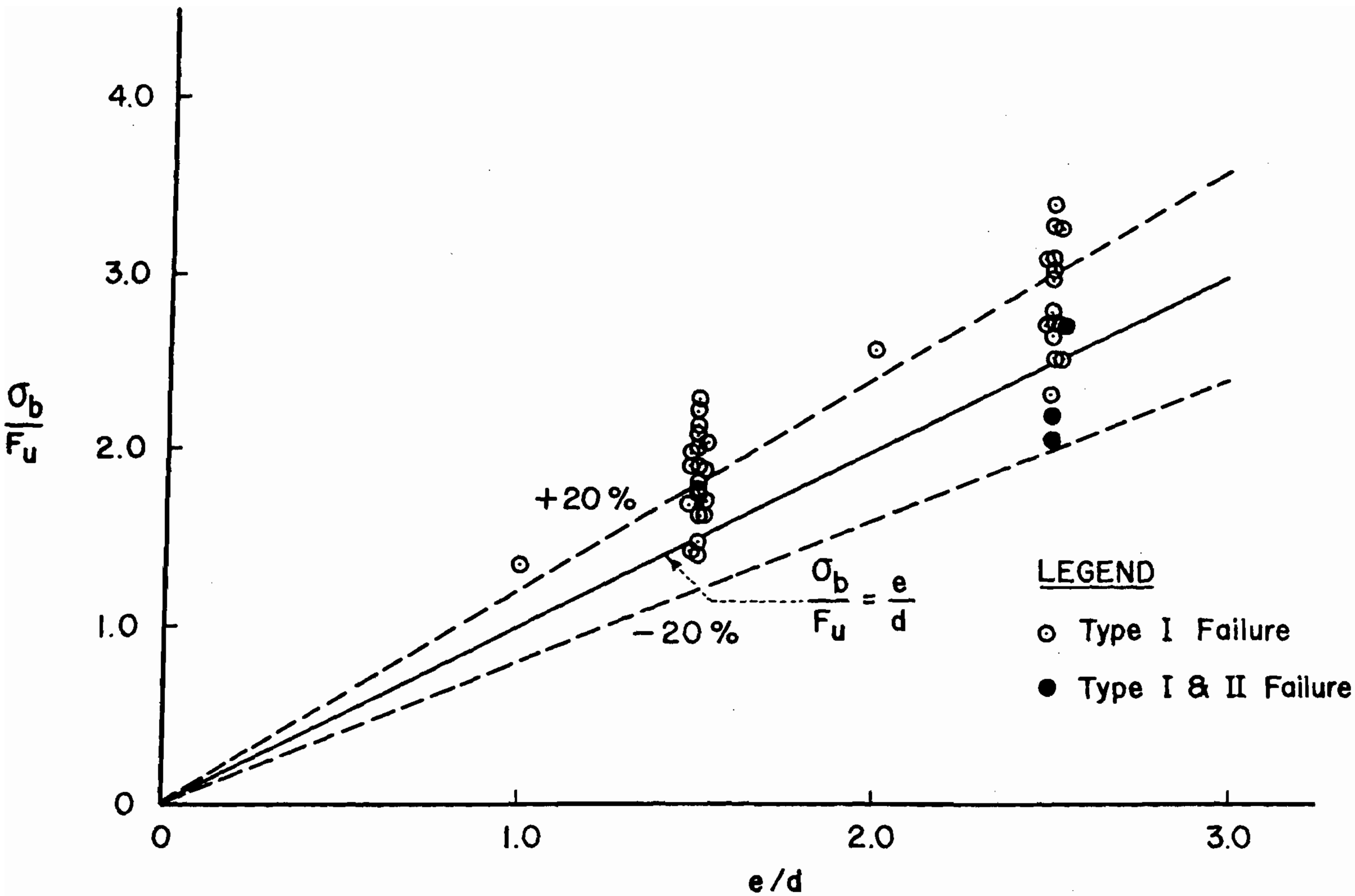

Fig. 2. Double Shear Connections with Washers, $\frac{F_u}{F_y} \geq 1.15$, e/d < 3.5, Shear Strength Study

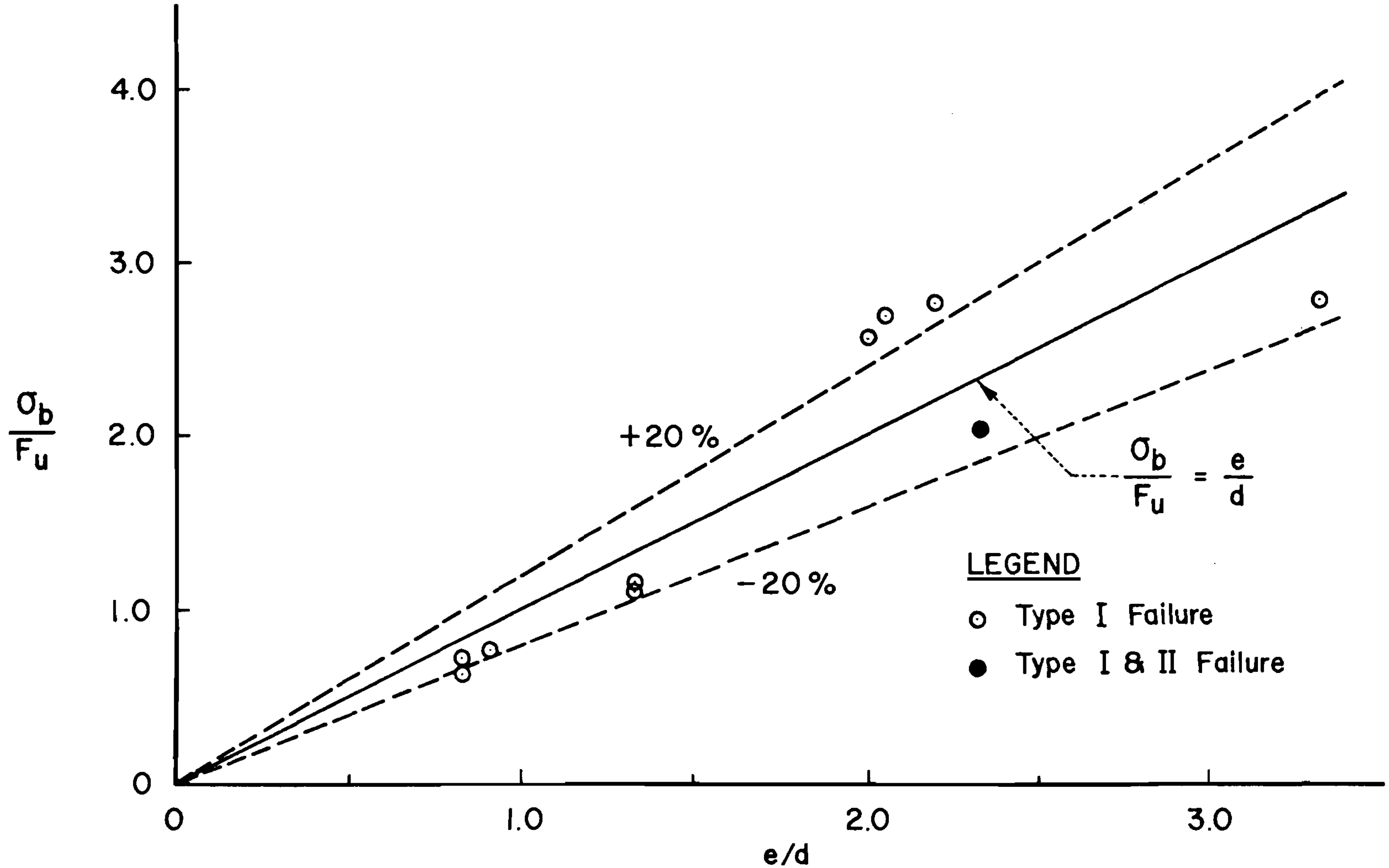

Fig. 3 Single Shear Connections with Washers, $F_u/F_y < 1.15$, $e/d < 3.5$, Shear Strength Study

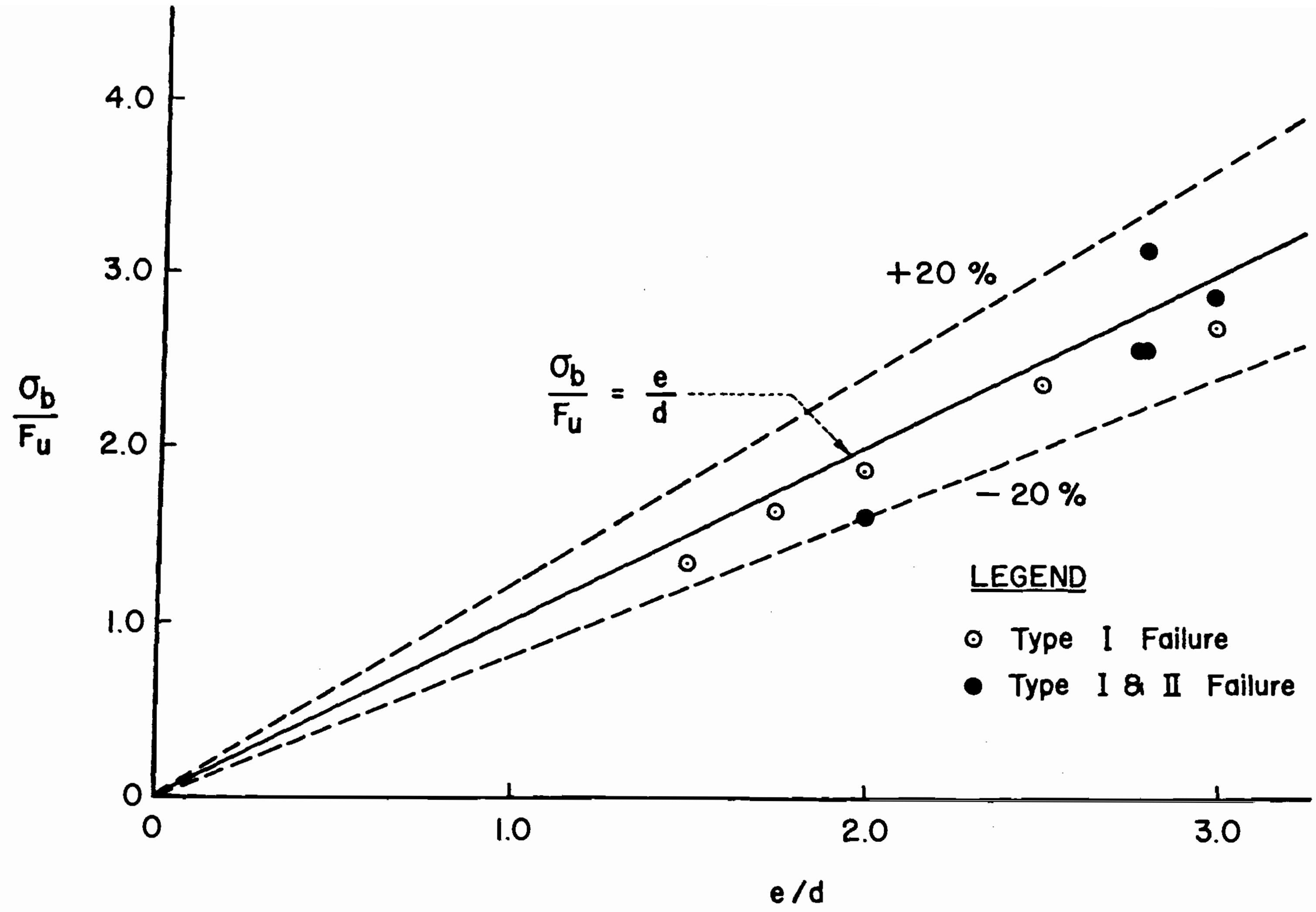

Fig. 4 Double Shear Connections with Washers, F_u/F_y <1.15, e/d < 3.5, Shear Strength Study

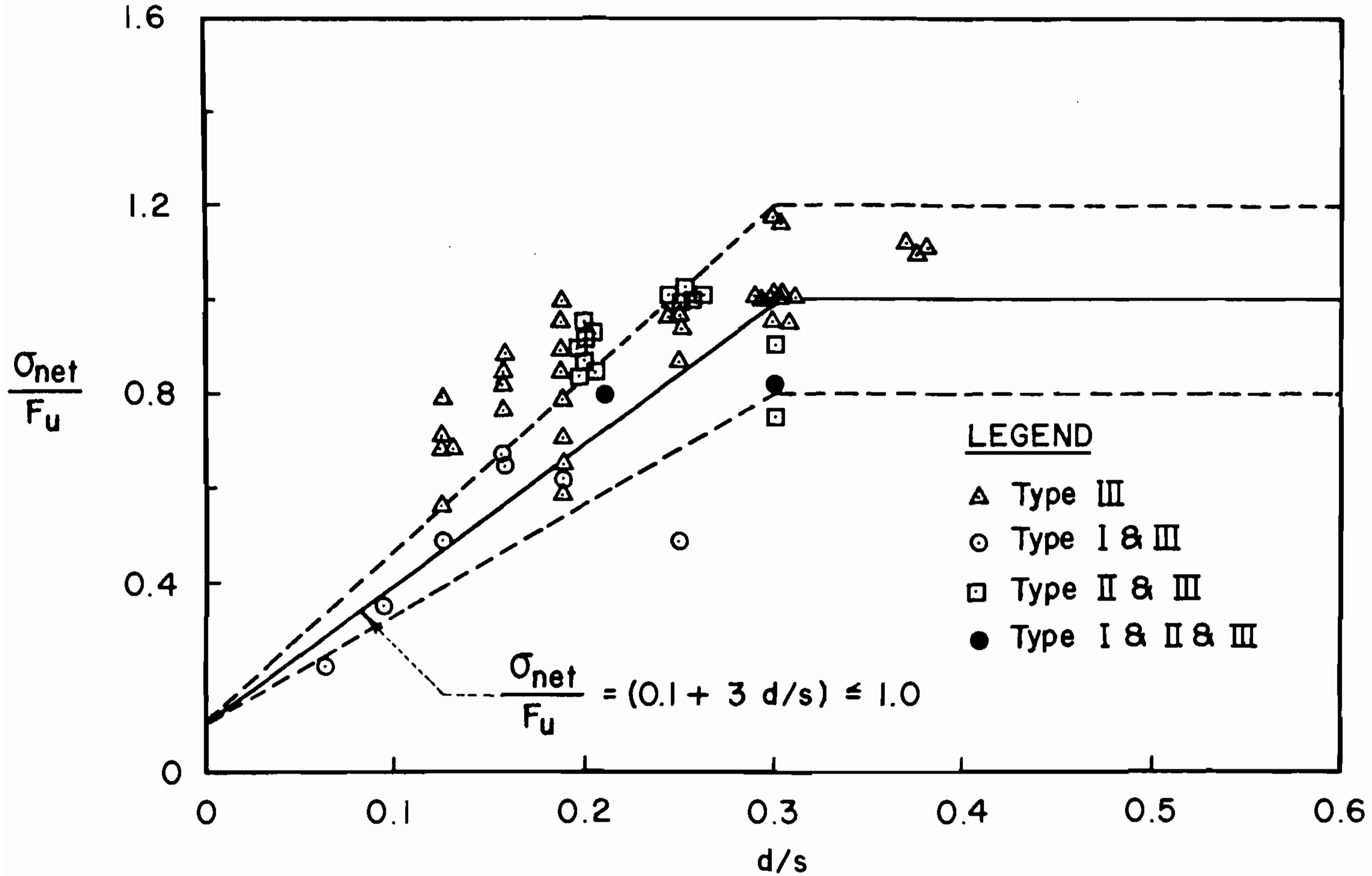

Fig. 5 (a) Effect of d/s on Tensile Strength of Bolted Connections with Washers (Double Shear, One Bolt)

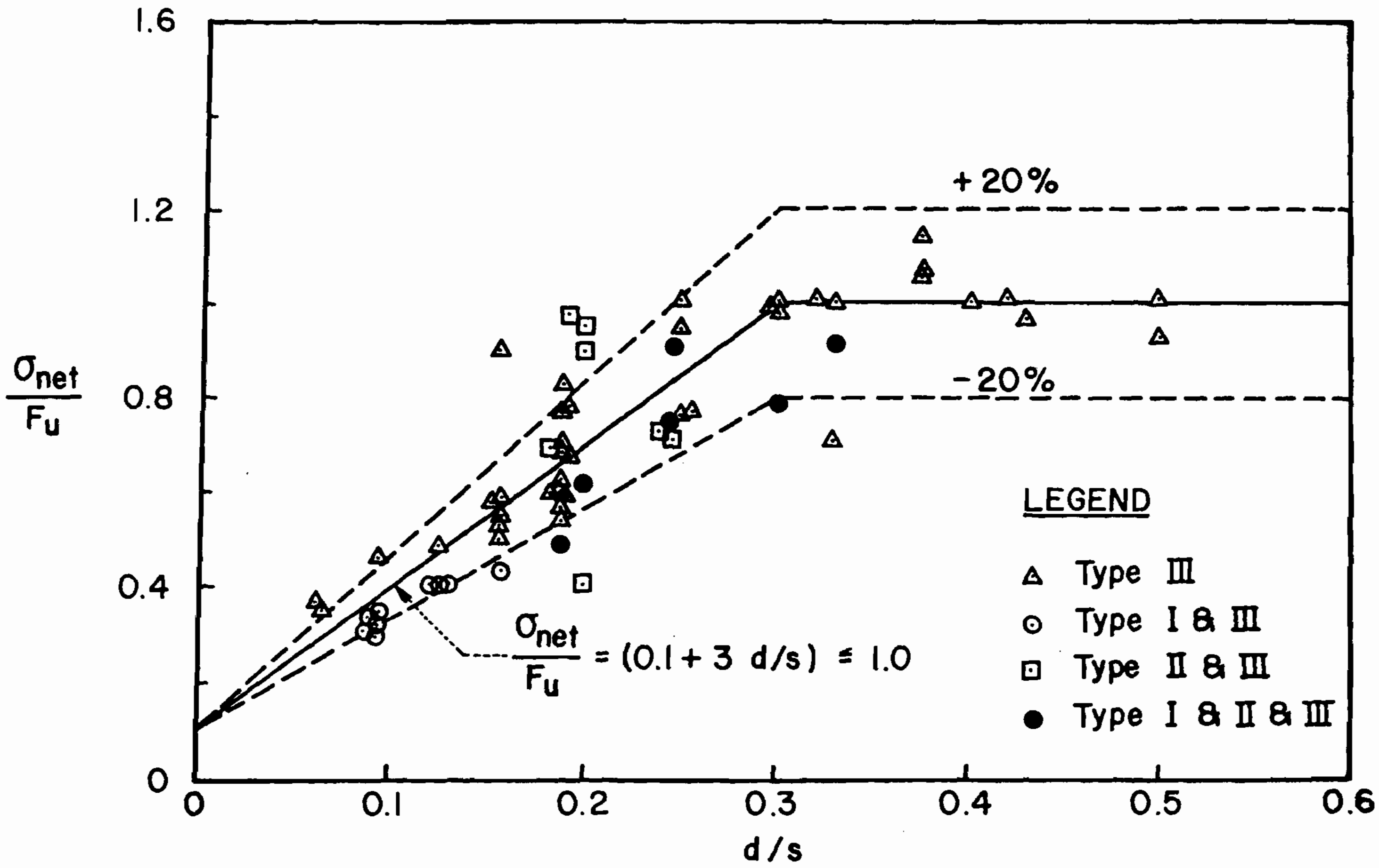

Fig. 5 (b) Effect of d/s on Tensile Strength of Bolted Connections with Washers (Single Shear, One Bolt)

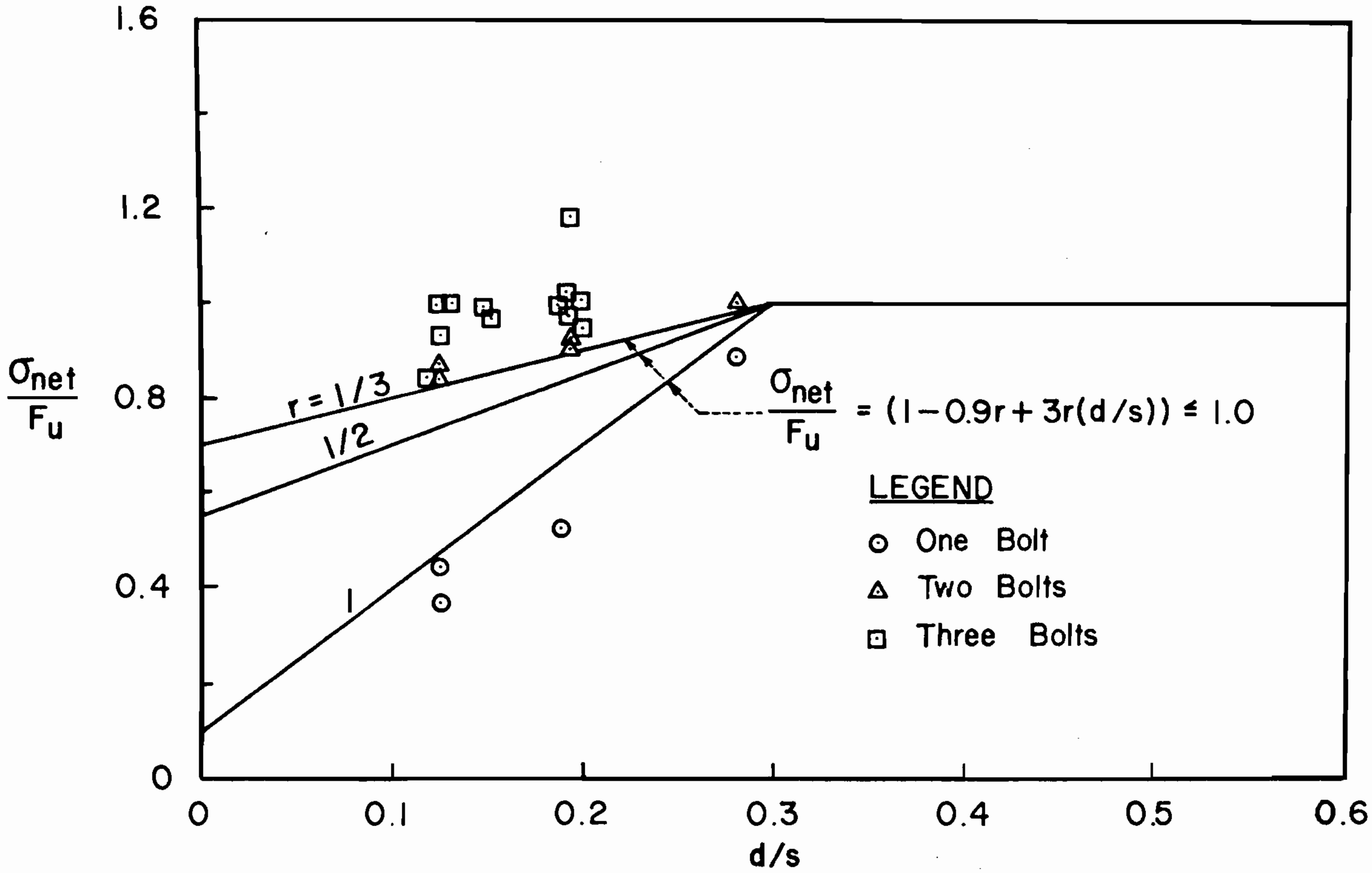

Fig. 5 (c) Effect of d/s on Tensile Strength of Bolted Connections (Single Shear, Multi-Bolt)[13]

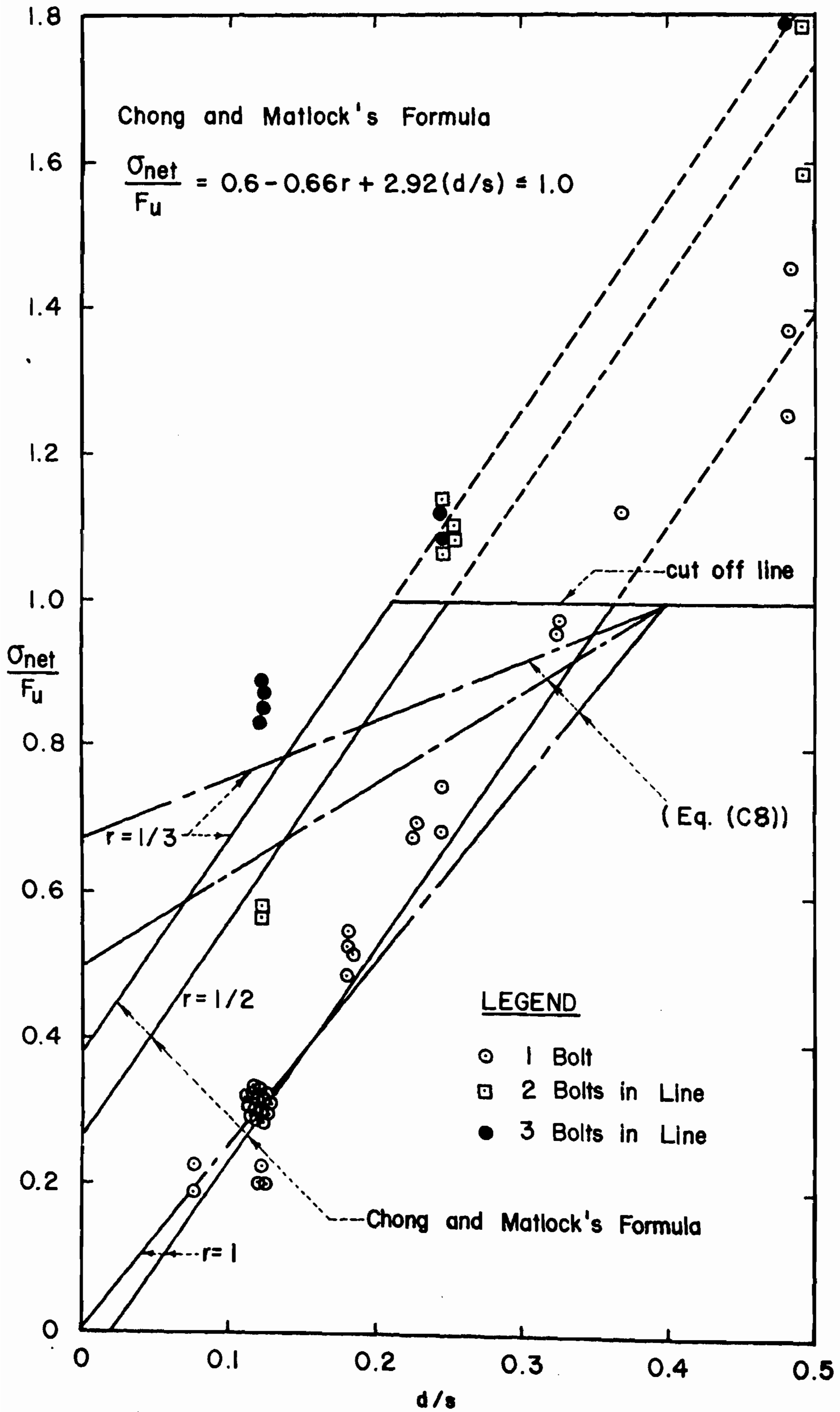

Fig. 6 Tensile Strength on Net Sections, Without Washers[11] (Single Shear Connections)

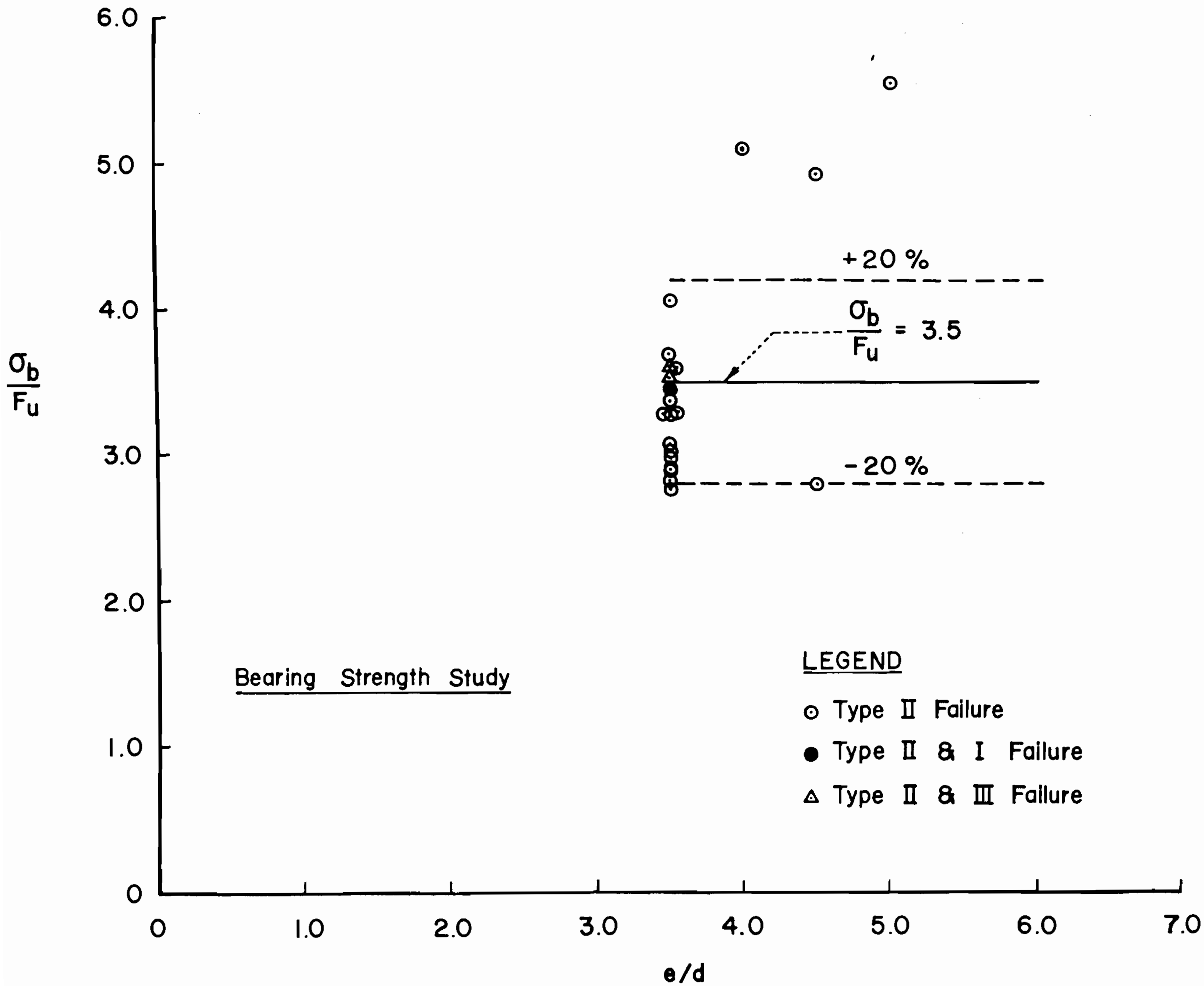

Fig. 7 Double Shear Connections with Washers, $F_u/F_y \geq 1.15$, $e/d \geq 3.5$

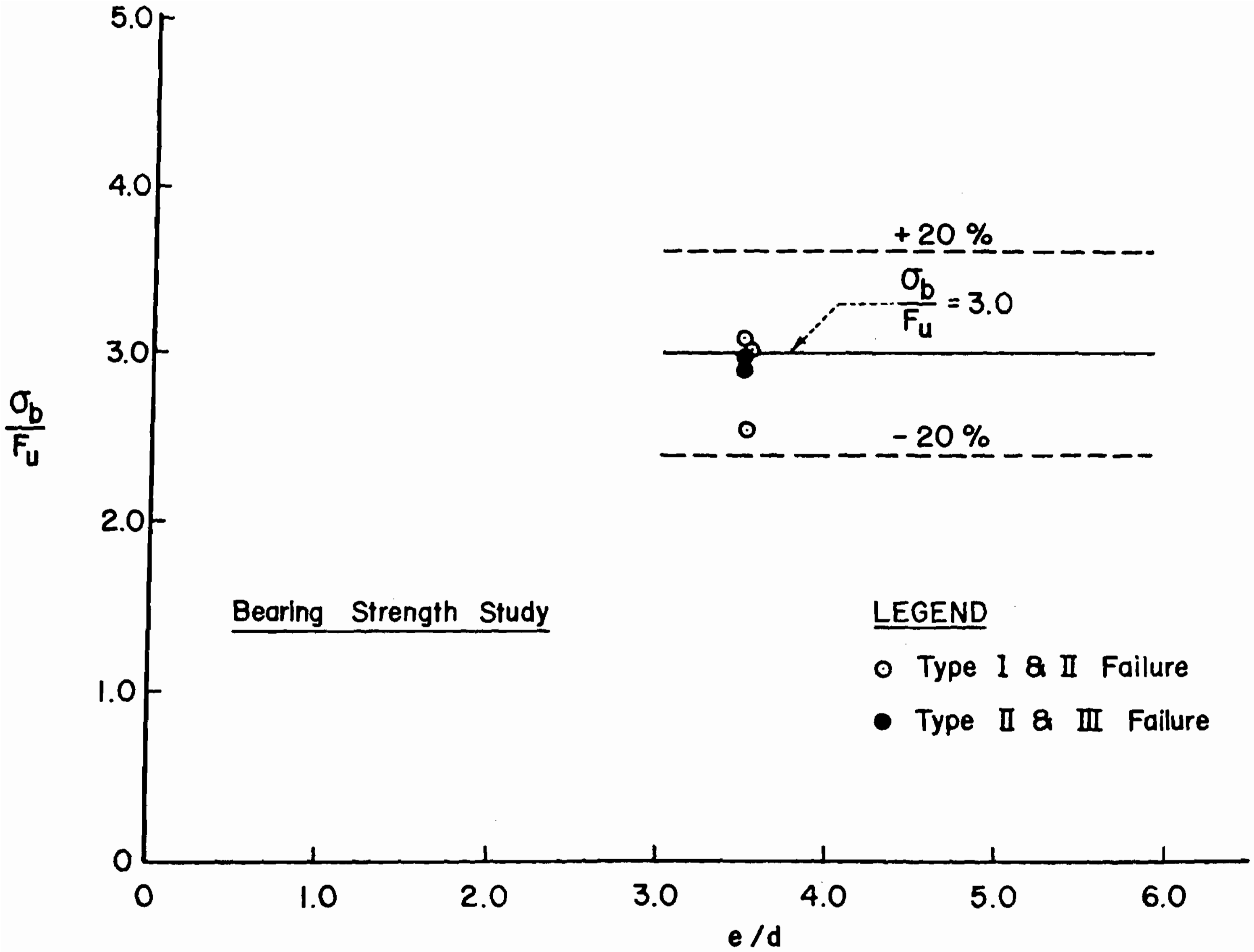

Fig. 8 Double Shear Connections with Washers, $F_u/F_y < 1.15$, $e/d \geq 3.5$

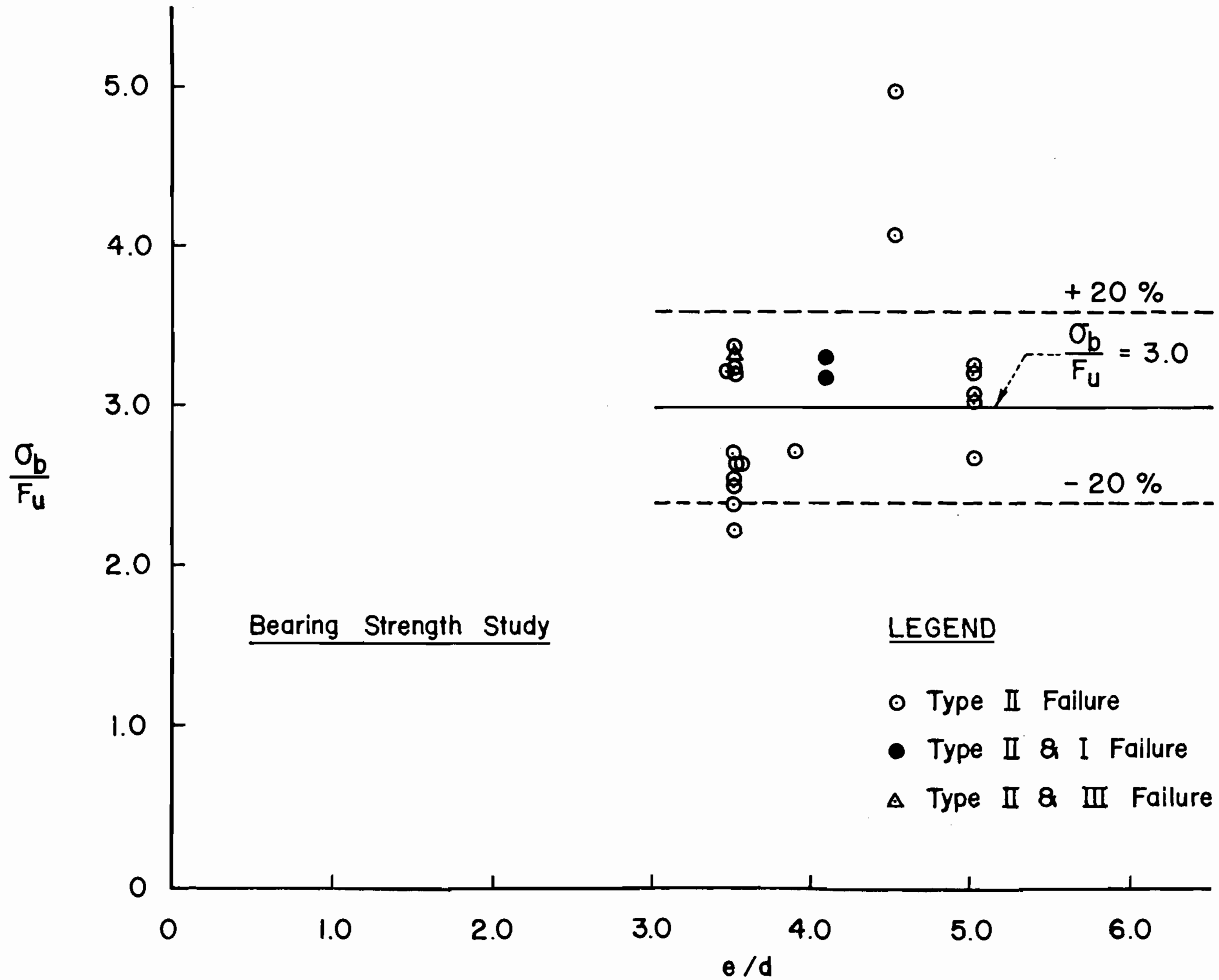

Fig. 9 Single Shear Connections with Washers, $F_u/F_y \geq 1.15$, $e/d \geq 3.5$

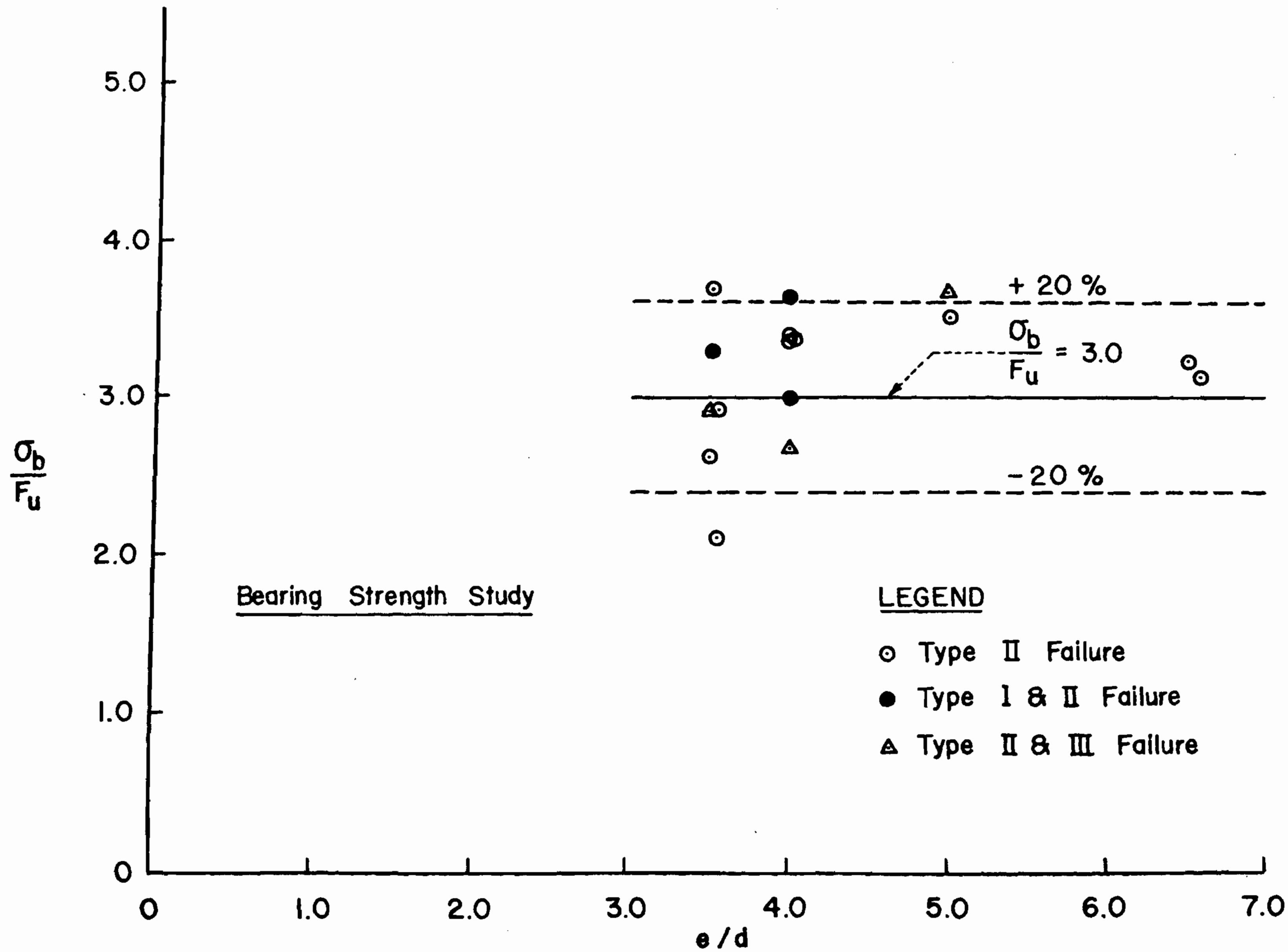

Fig. 10 Single Shear Connections with Washers, $F_u/F_y \leq 1.15$, $e/d \geq 3.5$

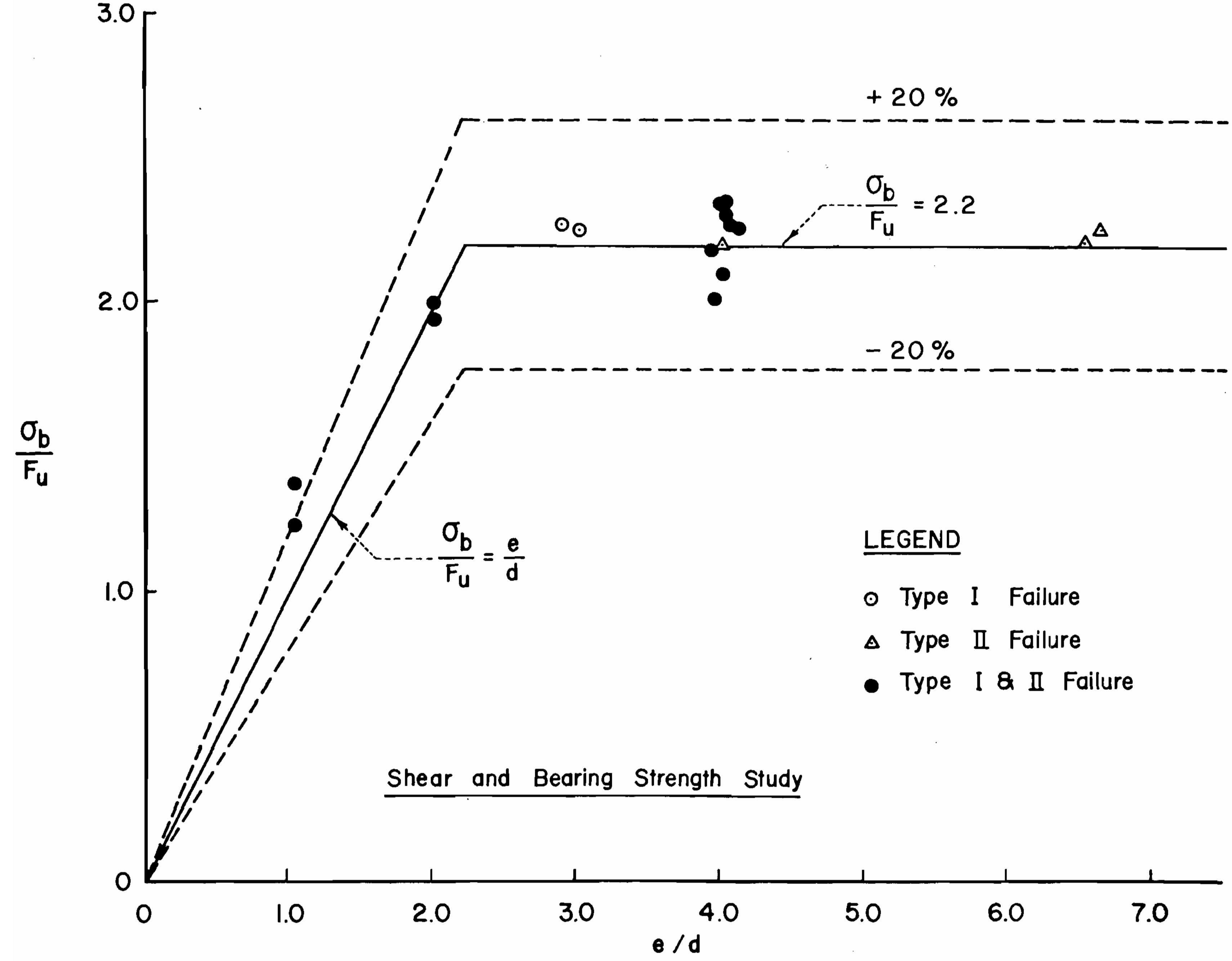

Fig. 11 Single Shear Connections without Washers, $F_u/F_y \geq 1.15$

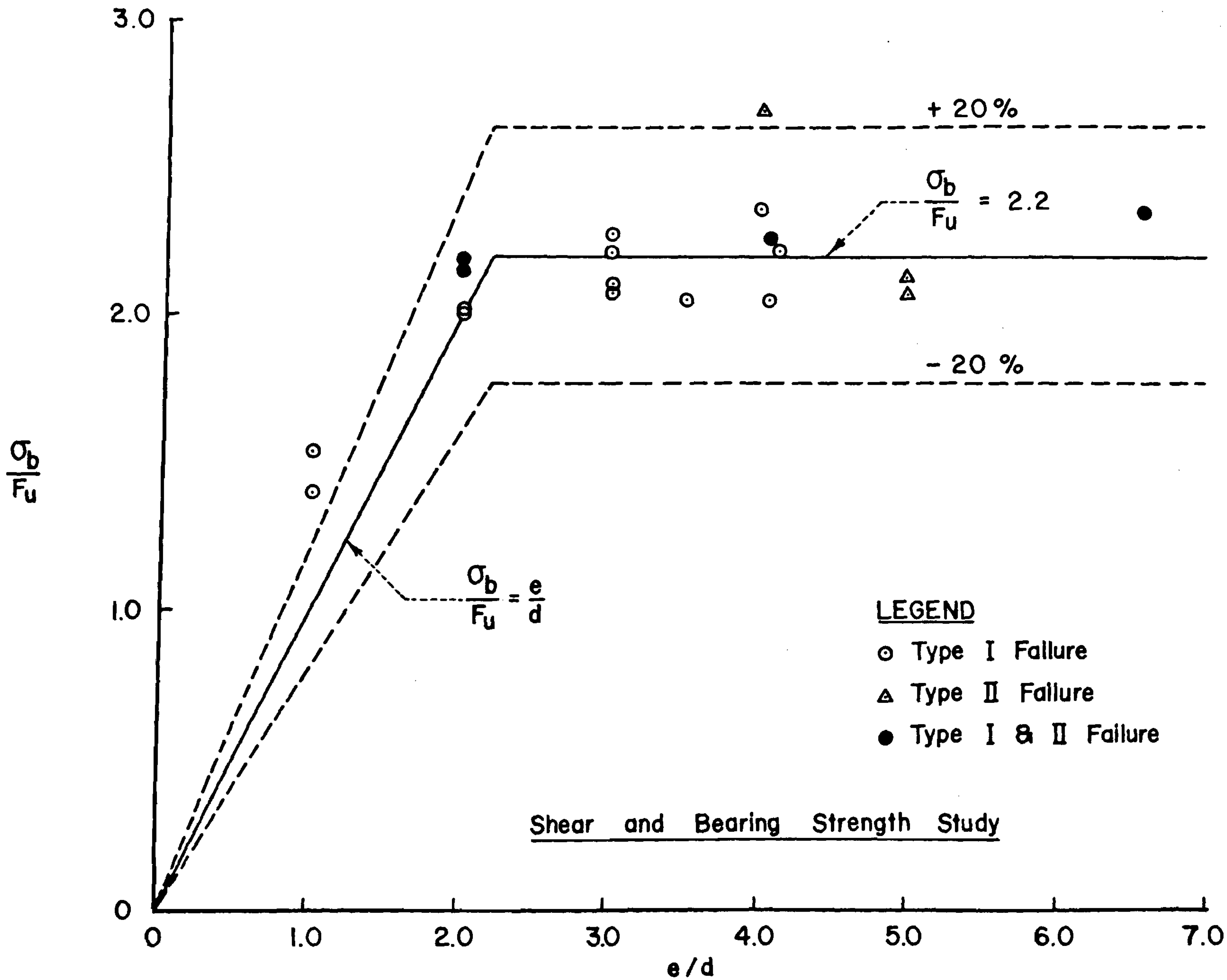

Fig. 12 Single Shear Connections without Washers, $F_u/F_y < 1.15$, $t \geq 0.036$ in.

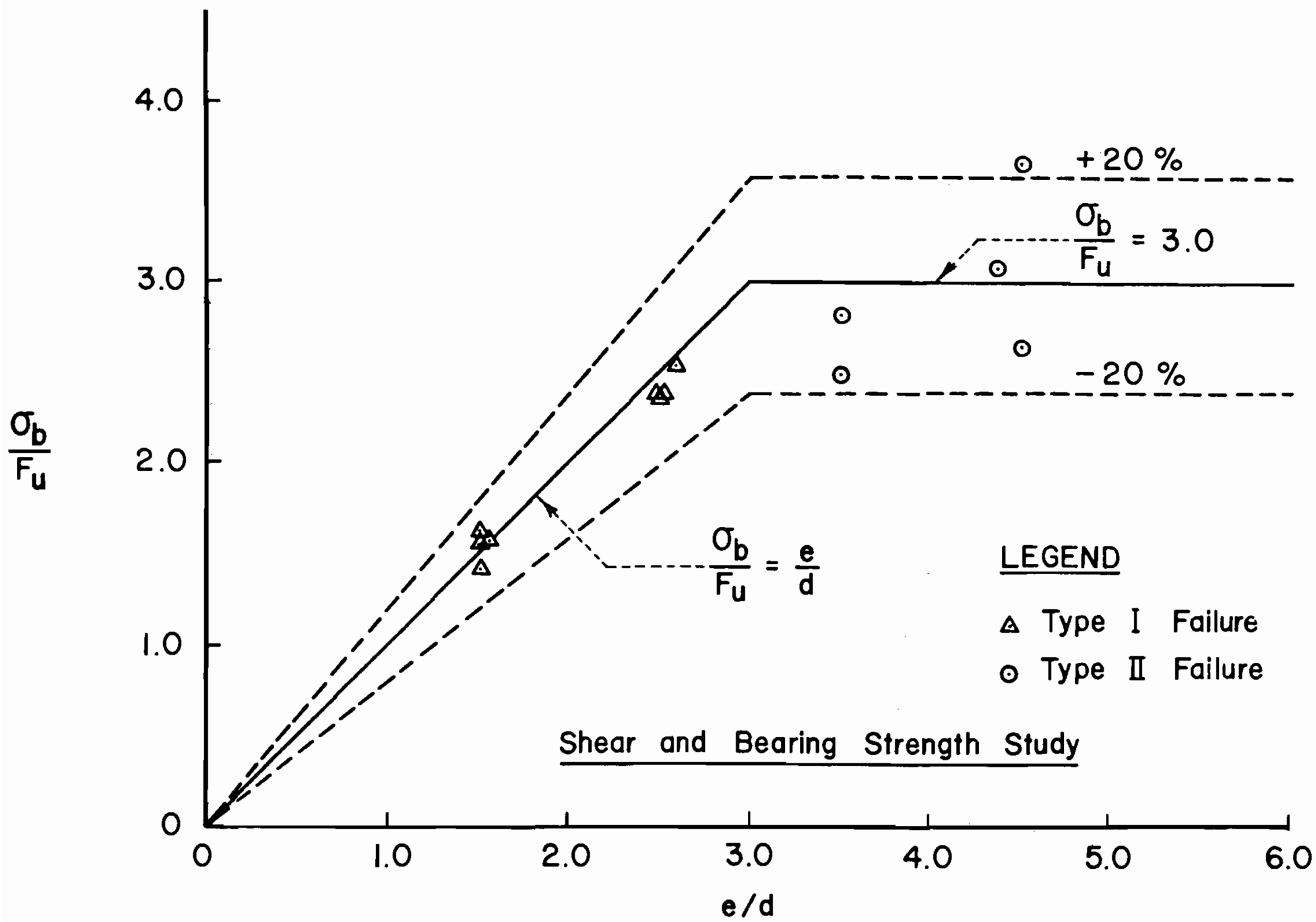

Fig. 13 Single Shear Connections with Washers, $F_u/F_y \geq 1.15$, $t \leq 0.036$ in.

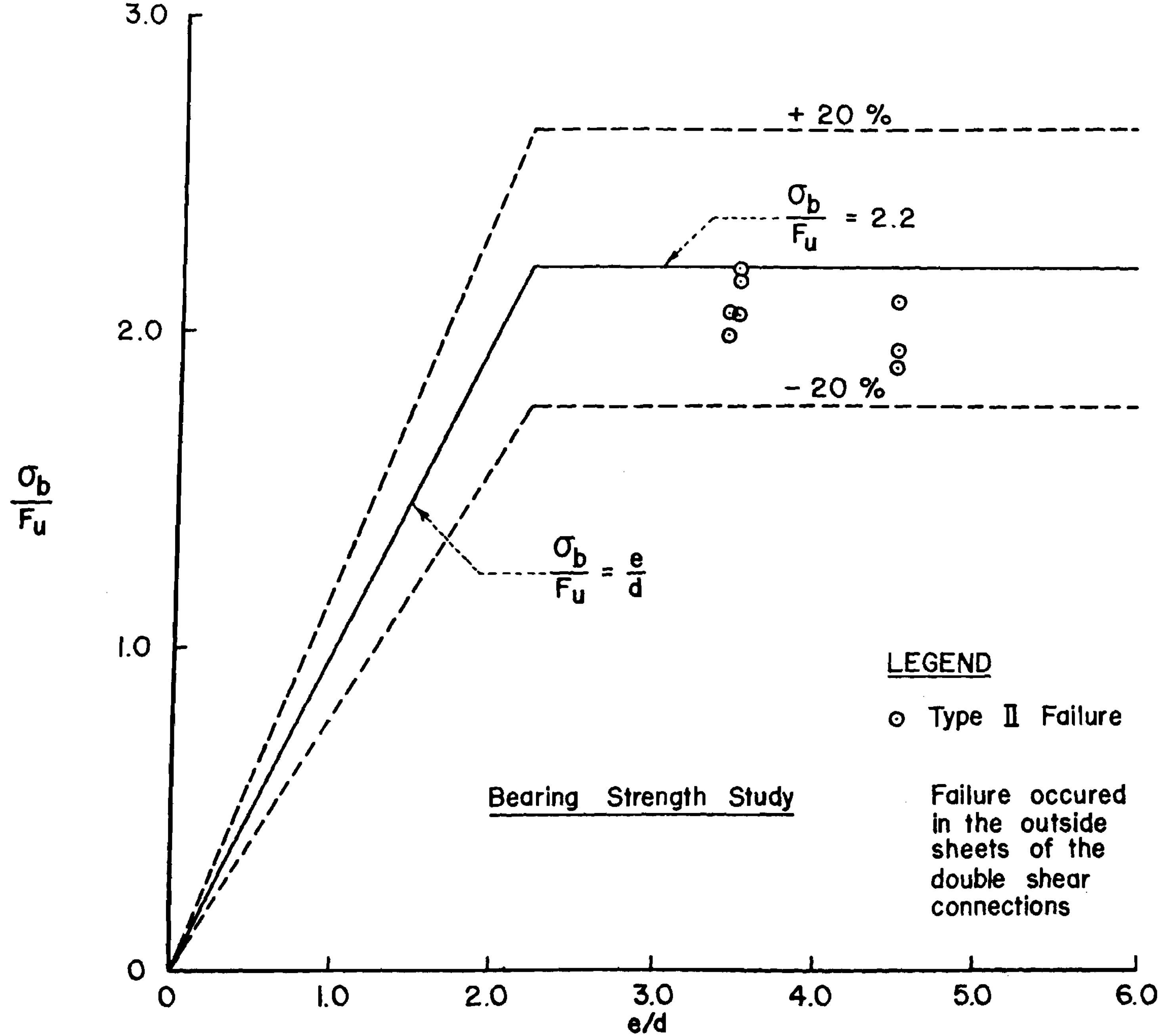

Fig. 14 Double Shear Connections without Washers, $F_u/F_y \geq 1.15$, $t \geq 0.036$ in.

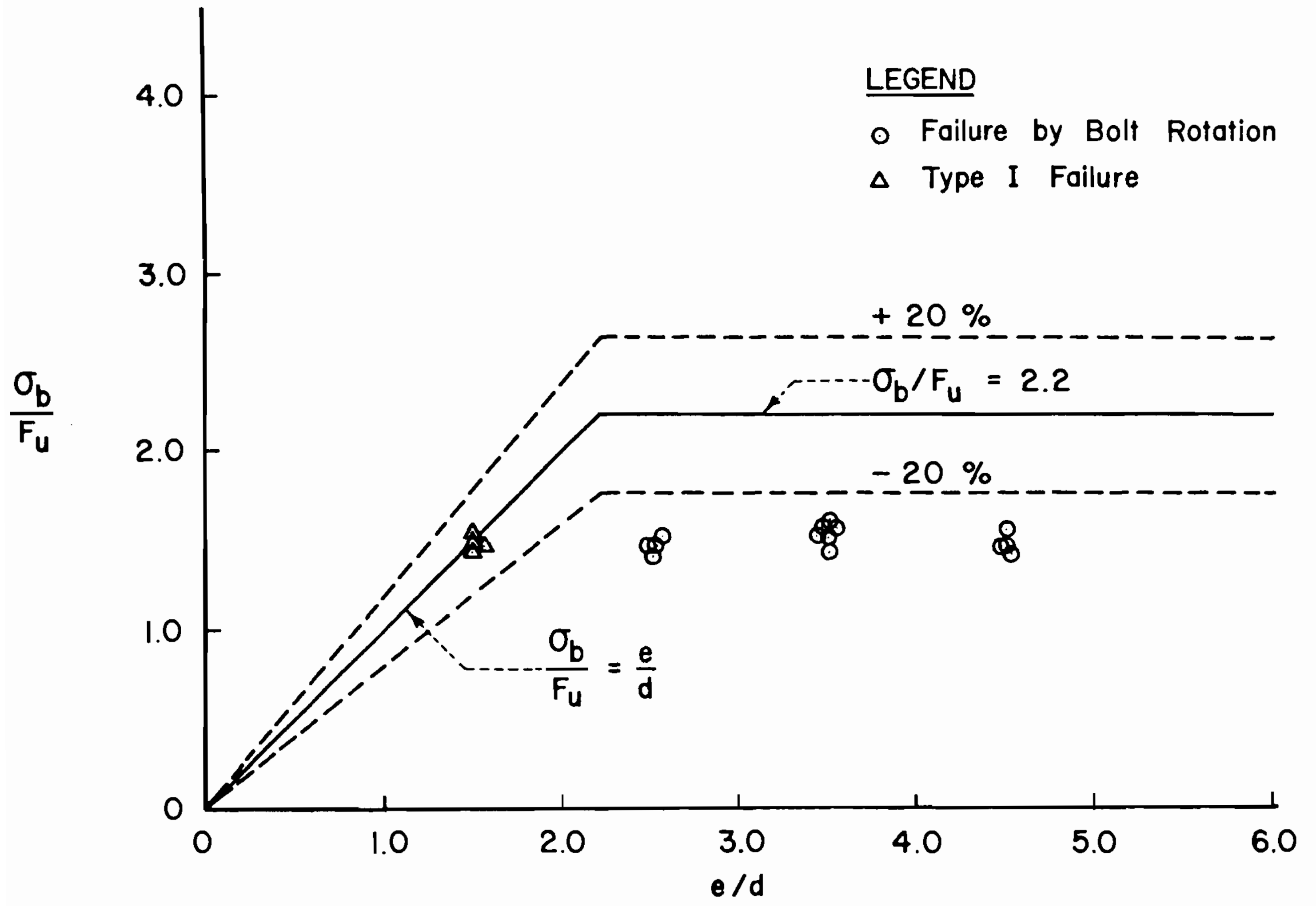

Fig. 15 Single Shear Connections without Washers, $F_u/F_y \geq 1.15$, $t \leq 0.036$ in.

APPENDICES

Department of Civil Engineering

University of Missouri-Rolla

FIRST PROGRESS REPORT

BOLTED CONNECTIONS IN COLD-FORMED STEEL STRUCTURES

by

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Research Assistant

Wei-Wen Yu

Project Director

A Research Project Sponsored by

American Iron and Steel Institute

Rolla, Missouri June, 1976

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I. INTRODUCTION

A. Purpose of Investigation

The design of bolted connections in cold-formed steel structures is based on the present AISI Specification for the Design of Cold-Formed Steel Structural Members.[1] Prior to the development of the design criteria, bolted connections were tested at University of Michigan[2] in the 1940's and then at Cornell University[3,4] in the 1950's. The present design provisions were developed primarily on the basis of the tests conducted by George Winter and his associates at Cornell University. Additional tests were recently made by Popowich[5] on multi-bolt connections and by Dhalla[6] on connections with low ductility steels. In these tests, the specimens were tightened to specified torques, and washers were placed under the head and nut of each bolt.

During recent years, bolted connections without washers have often been used in numerous instances. In some cases, the washers were used in the connections, but the bolts may not have been tightened according to the torques previously used in the Cornell tests. In order to study the effect of washers on connection strengths, Chong and Matlock[7] have conducted connection tests with and without washers. It was found that the bearing strengths of the connections were reduced considerably when the washers were eliminated. In addition, the parameters used by Chong and Matlock for evaluation of the tensile strength of bolted connections were slightly different from those used in the AISI Specification.

It is the purpose of this investigation to review the available test data first and then to study the applicability of the present design formulas to the connections that do not have washers and/or have improper torques.

Thin sheets will be used to make an additional study of the connection strength affected by the pretension of bolts and the behavior of bolted connections. In the study carried out to date, additional parameters, such as d/t and F_u/F_y ratios, have been considered for the evaluation of the connection strength.

B. Scope of Investigation

The present research project consists of an investigation of the structural behavior of bolted connections, a review of the current design criteria, and the conduct of additional tests to provide new design information if necessary. The following items have been planned for inclusion in this study: [20]

1) Analysis of available data
2) Effect of torque or pretension in bolts on bearing strength
3) Tensile strength of connections
4) Effect of d/t ratio on bearing strength, longitudinal shearing strength, and tensile strength of steel sheets
5) Difference between single shear and double shear conditions.

In order to achieve the objectives of the investigation, the planned research work includes the following three phases: [20]

1) Analysis of available data
2) Analytical and experimental investigation
3) Preparation of recommendations

Phase 1 of the investigation was initiated in February 1976. It was carried out by Randall L. Mosby, Research Assistant, and directed by Dr. Wei-Wen Yu, Professor of Civil Engineering at the University of Missouri-Rolla. Phases 2 and 3 will be conducted in future studies.

This progress report contains the results obtained from the analysis of the available data. It also includes the plans for future analytical and experimental investigations.

The research project was sponsored by American Iron and Steel Institute. The technical guidance provided by the AISI Task Group on Bolted Connections (L.W. Ife, T.J. Jones, R.B. Matlock, and D.S. Wolford, members) and the AISI Staff (A.L. Johnson and D.P. Cassidy) is gratefully acknowledged. Thanks are also due to J.H. Senne, Chairman of the Department of Civil Engineering, for his advice. Acknowledgment is also due to E.B. Gibson, past Chairman of the AISI Task Group, for his technical guidance.

II. ANALYSES OF AVAILABLE DATA

From the Cornell investigation, Winter[3,4] observed that there are four distinct types of failure modes in bolted connections:

TYPE I - Longitudinal shearing of the steel sheet along two practically parallel planes whose distance of separation equals the bolt diameter.

TYPE II - Shearing-tearing along two distinctly inclined planes accompanied by a considerable "piling-up" of the material in front of the bolt, or bearing failure.

TYPE III - Transverse tension-tearing across the sheet.

TYPE IV - Shearing of the bolt.

In order to provide the needed additional information on the strength of bolted connections, as discussed in Article I.A., these four types of failure have been reviewed in detail.

During the review and evaluation of the available data, due consideration was given to the following factors that may affect the load-carrying capacities of bolted connections:[20]

a. Torques or pretension used in installation of bolts

b. Ratios of e/d, d/s, and d/t

c. Use of washers

d. Single and double shear conditions

e. Number of rows perpendicular and/or parallel to the line of stress

f. Ductility of material or the effect of F_u/F_y

In the above listed factors, all symbols are defined as follows:

e = edge distance, in.

d = diameter of the bolt, in.

s = spacing of bolts normal to the direction of force - for a single bo

it is the full width of connected sheet, in.

t = thickness of connected sheet, in.

F_u = ultimate tensile stress of sheet, ksi

F_y = yield point of steel, sheet, ksi

A. Ductility of Material

Ductility is the ability of a material to undergo plastic deformation without fracture. It can be measured by the permanent elongation of a tensile specimen after fracture. This property enables the steel to redistribute the stress when a certain part of the member yields locally.

Based on his study conducted at Cornell University, Dhalla[6,12,13] indicated that the structural strength of a bolted connection is one of the most critical problems for low-ductility steels. For the design of bolted connections, the present AISI[1] Specification states in Section 4.5 that if the ratio of tensile strength to yield point is less than 1.35, a stress equal to the minimum tensile strength of the material divided by 1.35 shall be used instead of F_y. This is an additional provision concerning the ductility of the steel to maintain a minimum safety factor of 2.2.

On the basis of Dhalla's findings, Liu[14] showed that the results of bearing tests involving both high-ductility and low ductility steels can be predicted by a single formula if a proper ductility factor is used. This factor can be determined as follows:

(a) $C_2=1$, for $F_u/F_y \geq 1.35$ (1)

(b) $C_2=1.43\ (F_u/F_y)-0.93 \geq 0.643$, for

$$1.05 < F_u/F_y < 1.35\ . \qquad (2)$$

Table 1 contains the test results obtained by Dhalla[6]. The results involve both high-ductility and low-ductility steels, and the F_u/F_y ratios range from 1.57 to 1.04. These data are plotted in Figures 1, 2, and 3 for different tensile strength to yield point ratios. In order to show the effectiveness of the ductility factor, Dhalla's data have been replotted in Figure 4. By using C_2, as determined by Equation (1) and (2), good correlation can be found between Winter's tests on high-ductility steels and Dhalla's tests on low-ductility steels.

B. Bearing Strength

1. General

Based on the tests performed at Cornell[8,9,10,11], Winter[3,4] concluded that when the edge distance of a bolt connection is relatively large a type of failure by bearing will control the load carrying capacity of the connection. Test results indicate that when the e/d ratio equals or exceeds 3.5 the bearing stress can be conservatively determined by Eq. (3):

$$\sigma_b = 4.9\ F_y \qquad (3)$$

where σ_b = ultimate bearing stress, ksi.

The AISI[1] design equation for allowable bearing stress for thin, cold-formed steels is derived from Eq. (3) by applying a safety factor of 2.33, i.e.,

$$F_p = 2.1\ F_y \qquad (4)$$

where F_p = allowable bearing stress, ksi.

As previously discussed in Section II.A., the ductility of steel is an important parameter for the bearing strength of a bolted connection. From the study made by Liu,[14] the following modified equations can be used to determine the ultimate and allowable bearing stresses for any type of steel:

$$\sigma_b = 4.9\ C_2 F_y \tag{5}$$

$$F_p = 2.1\ C_2 F_y^*. \tag{6}$$

The factor C_2 can be determined by Eqs. (1) and (2), whichever is applicable.

2. Torque Used in Installation

The present design provisions governing the bearing strength of a bolted connection are based on the early tests performed at Cornell,[8,9,10,11] for which all the bolts were torqued to the specified values. The torques used for ordinary A307 bolts are given in Table 13. Table 14 is a list of the torques used for high strength A325 bolts. The additional research of Popowich[5], Dhalla[6], and Chong and Matlock[7], is also based on these torques.

In the investigation of Liu[14], the torques used for the high strength bolts were the same as those used for the A307 ordinary bolts. This was done in a hope that the high-strength bolts would behave in the same was as ordinary bolts insofar as the bearing capacity between the connected part and bolt was concerned. Even though no specific conclusion was drawn for the effect of low values on bearing strength, satisfactory results have been obtained by using the specified minimum torques.

---

*Recommended in Ref. 22.

Because the effect of torques on the bearing strength of bolted connections has not been fully studied in the past, further investigation should be carried out in this area.

Recently, there have been indications that the minimum torque requirements do not guarantee the proper tension in the bolts. Consequently, the test data often show inconsistent results. In view of the fact that the method of installation of high strength bolts for thick hot-rolled shapes cannot be directly used for thin, cold-formed sections due to the differences in grip length and size of bolts, a new method of installation should be developed.

3. Effect of e/d Ratio

As mentioned in the previous section, when the e/d ratio is equal to or greater than 3.5 the strength of connection is limited by the bearing capacity determined by Eq. (5). Test results indicate that when the e/d ratio is less than 3.5 longitudinal shearing of the steel sheets will occur. This type of shearing failure is discussed in Section II.C.

The present AISI design equation for the determination of the bearing stress applies to both single and double shear connections. In order to verify the use of Eq. (5) to both types of connections, test data obtained from Cornell[8,9,10,11], Dhalla[6], Liu,[14] and Chong and Matlock[7] have been analyzed and are given in Tables 2, 3, and 4. A graph of σ_b/C_2F_y vs. e/d, which has been constructed with these data, is shown in Fig. 5.

It can be seen that when e/d is equal to 3.5, the experimental values of σ_b/C_2F_y for both single and double shear connections can be predicted by Eq.(5). For larger e/d ratios, Eq. (5) provides a better prediction of σ_b/C_2F_y for single shear connections than double shear connections. The double shear condition gives a more conservative result on bearing strength.

It should be noted that by using the ductility factor C_2, determined by Eqs. (1) and (2), Eq. (5) can be generalized for both high-and-low-ductility steels.

4. Effect of d/t Ratio

The present design equation for bearing stress has been developed for e/d $\geq$ 3.5. Since the diameter of the bolt to the thickness of the material ratio, d/t, is much larger for cold-formed steel connections than hot-rolled shapes, it was believed that the d/t ratio might affect the bearing strength of the connection. In order to study the effect of the d/t ratio on the bearing strength, the test data obtained from previous work [6-11,14] were analyzed and are listed in Tables 2, 3, and 4 of Appendix B. These results of tests were obtained from specimens with e/d ratios greater than 3.5 that failed either in bearing or a combination of bearing and other type of failure.

For single shear connections, the ratio of bearing stress at failure to yield point, σ_b/C_2F_y, has been plotted versus d/t as shown in Fig. 6. From a least squares analysis, the following equation was obtained:

$$\sigma_b/C_2F_y = 4.31 + 0.071\ d/t. \qquad (7)$$

From Eq. (7) it can be seen that as the d/t ratio increases there is a slight increase in the bearing stress. However, for double shear connections, Eq. (8) shows that the bearing stress decreases slightly as the d/t ratio increases;

$$\sigma_b/C_2F_y = 5.35 - 0.03\ d/t. \quad (8)$$

Even though Eqs. (7) and (8) may be used to predict the changes in the bearing stress for the increase of d/t, the effect of d/t is considered to be relatively small. It should be noted that in the region of $9 \leq d/t \leq 15$ only a limited amount of data are available for a detailed study. It appears that further investigation might be needed for this region of d/t ratio.

For single shear connections without washers, no significant effect was noted on the bearing stress for various d/t ratios as shown in Fig. 8.

5. Effect of Washers

The present design provisions for the bearing stress of bolt connections in cold-formed steel design are based on the tests performed at Cornell on specimens with washers both under bolt head and nut. In order to study the effect of washers on bearing strength of connections, Chong and Matlock[7] conducted a study of bolted connections without washers, for which the maximum bearing stress at failure was found to be about 45% less than those with washers. Consequently, Eq. (9) was proposed in Ref. 7 for the prediction of the ultimate bearing stress of connections without washers;

$$\sigma_b = 2.7\ F_y \quad \text{for } e/d > 2.5. \quad (9)$$

It should be noted that for connections without washers a bearing type of failure will occur for small e/d ratios as compared to the connections with washers.

If one considers the effect of ductility on bearing strength of bolted connections, Eq. (9) may be modified by using the C_2 factor as shown in Eq. (10);

$$\sigma_b = 3.5\ C_2 F_y \quad \text{for } e/d > 2.5. \tag{10}$$

The correlations of the tested bearing strengths and the predicted values on the basis of Eq. (10) are shown graphically in Fig. 9. Table 4 gives the mean value and standard deviation of the ratios between the computed and tested results.

By using a safety factor of 2.3, the allowable bearing stress for bolted connections without washers can be determined as follows:

$$F_p = 1.5\ C_2 F_y \quad \text{for } e/d > 2.5^{*} \tag{11}$$

6. Tentative Recommendations

As stated earlier, Dhalla[6] has indicated that the ductility of the steel affects the strength of a bolted connection particularly for bearing capacity. It appears that the present design equation for the determination of bearing stress may be modified by using the C_2 factor as shown in Eqs. (6) and (11) for bolted connections with and without washers, respectively.

A review of the available data indicates that the effect of torque on the bearing strength of bolted connections has not been fully investigated. A study of the effect of torque or pretension in bolts may include the following conditions, which were proposed in Reference 20:

a. No torque or pretension in bolts

b. With the same pretension in bolts as specified by the Research Council on Riveted and Bolted Structural Joints (Table 15)

*Recommended in Ref. 22.

c. With the same torque used in the previous Cornell Tests (Table 12)

The test data obtained from Case (c) above will be compared with those obtained from Cases (a) and (b).

It has been shown from the available data that the d/t ratio has little effect on the bearing strength. However, further study appears to be needed in the region of d/t ratios from 9.0 to 15.0.

Based on their investigation of bolted connections without washers, Chong and Matlock[7] concluded that the bearing strength is actually 45% less than that for connections with washers. However, if the ductility of steel is considered, the bearing strength is found to be 29% less than that with washers. It should also be noted that the test specimens used by Chong and Matlock consisted of single shear connections only. Further study should be conducted for both single and double shear connections without washers and for connections using steel sheets thinner than 0.036 in.

C. Longitudinal Shearing Strength of Steel Sheets

1. General

As discussed in the preceding section, if the edge distance in line of stress is insufficient, longitudinal shearing of the connected sheets will occur along two practically parallel planes. Based on his research work, Winter concluded that when the e/d ratio is less than about 3.5, the bearing stress to yield point ratio increases with the increasing e/d. It can conservatively be represented by the following straight line equation:

$$\sigma_b/F_y = 1.4\ e/d. \tag{12}$$

By inserting $\sigma_b = P_u/dt$ into Eq. (12), (P_u being the failure load, per bolt), the nominal shear stress in the two failure planes can be determined by Eq. (13):

$$\tau_s = P_u/2te = 0.7\ F_y. \tag{13}$$

By applying the ductility constant C_2 as determined by Eqs. (1) and (2), the following modified equation can be used to predict the shear strength of a bolted connection:

$$\tau_s = 0.7\ C_2 F_y \quad \text{for } e/d < 3.5. \tag{14}$$

2. Torque Used in Installation

As mentioned in Section II.B.2, in the majority of the tests performed on bolted connections, A307 and A325 bolts that have been torqued to the specified values have been used. The exact effect of torque on the bearing strength is a specific area of needed research. It has been shown by Winter that for connections with e/d ratios less than 3.5 a shearing type of failure will occur if washers are used under both head and nut. This conclusion is based on the results of tests for which the bolts were torqued to the specified values as given in Tables 13 and 14.

When bolted connections with e/d ratios less than 3.5 and bolts with torques that satisfy the specified values are used, a shear type of failure may be prevented because the friction between the connected sheets is increased and causes a larger failure load.

Because there is not sufficient data concerning the effects of torque on the shearing strength of steel sheets of a bolted connection, further tests are needed in this area.

3. Effect of e/d Ratio

As pointed out in Section II.C.1, Eqs. (12) and (14) are valid only when e/d does not exceed 3.5. Within this range, the structural strength of the bolted connection is governed by a longitudinal shearing type of failure.

In the AISI Specification, Equations (12) and (14) are presently used for both single and double shear connections. In order to determine the possible differences between these two types of connections, the test data obtained from previous investigations[6-11,14] have been analyzed and are given in Tables 5, 6, and 7. These data deal with the specimens that have failed in longitudinal shearing of the sheets with e/d ratios less than 3.5.

Figures 10 and 11 show the correlation between the test data and the predicted values for single and double shear connections, respectively. Because the ductility factor, C_2, is used in the ratio of bearing stress to yield point, both high- and low-ductility steels can be combined in the same graph.

It can be seen from Figs. 10 and 11 that most of the test data for both single and double shear connections is on the conservative side of that predicted by Eq. (12). There is no major difference for the two types of connections.

4. Effect of d/t Ratio

As mentioned in Article II.B.3, there is a question concerning the effect of the d/t ratio on the bearing strength of a bolted connection. From the studies made on bearing strength, it has been found that for connections with e/d ratios larger than 3.5, the effect of d/t is negligible. However, further investigation may be needed for connections with d/t ratios from 9 to 15.

In order to study the effect of d/t on connections with e/d ratios less than 3.5, the available data[6-11,14] have been analyzed and are given in Tables 5, 6, and 7. In Figs. 12 through 15, the tested data have been plotted separately according to the single or double shear type of connections and to the actual value of the e/d ratios.

For the single shear connections with e/d equal to 1.5, it can be seen from Fig. 12 that the actual bearing stress at the failure load resulting from the shearing strength of the steel sheets is not affected by the d/t ratios. But, for the double shear connections with the same e/d ratio of 1.5, there is a slight increase in the bearing stress for an increase in the d/t ratio as shown in Fig. 13. The effect of d/t can be described by the following equation:

$$\sigma_b/C_2F_y = 2.47 + 0.024\ d/t. \qquad (15)$$

When the e/d ratio is increased to 2.5, it can be seen from Fig. 14 that the d/t ratio does not affect the bearing stress in single shear connections. However, for the double shear connections with the same e/d ratio, test data show a slight decrease in the bearing stress for increasing d/t. See Fig. 15. The following equation can be used to determine the effect of d/t ratio on bearing stress, σ_b:

$$\frac{\sigma_b}{C_2F_y} = 4.22 - 0.04\ d/t. \qquad (16)$$

5. Effect of Washers

The present equation used for the determination of the shearing strength of steel sheets of a bolted connection is based on the test specimens that have had washers placed under both the heads and nuts of the bolts. From Chong and Matlock's[7] study on bolted connections without washers, it has been found that the shear stress in steel sheets at failure is less than that for connections with washers. Consequently, for bolted connections with e/d ratios less than 2.5, the bearing stress can be determined as follows:

$$\frac{\sigma_b}{F_y} = 1.08\ (e/d). \tag{17}$$

Because $\sigma_b = P_u/dt$, then at failure the shear stress in the two parallel planes of the steel sheets is

$$\tau_s = \frac{P_u}{2te} = 0.54\ F_y. \tag{18}$$

The above equation indicates a 23% reduction in shear strength when washers are not used.

Considering the actual ductility of steel, Eq. (17) may be modified by using a factor C_2 as follows:

$$\frac{\sigma_b}{C_2F_y} = 1.4\ (e/d). \tag{19}$$

The comparisons of the test results and the predicted values are shown in Fig. 16 . Based on Eq. (19) and a factor of safety of 2.3, the following design equation can be used for the determination of the minimum edge distance in lieu of stress when e/d $\leq$ 2.5:

$$e_{min} = P/(0.6\ C_2F_yt)^{*} \tag{20}$$

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*Recommended in Ref. 22.

6. Tentative Recommendations

As a result of the difference in ductility of various types of steels, the AISI requirement for the minimum spacing and edge distance of a bolted connection can be modified by using the ductility factor, C_2, as discussed in Sections II.A and II.C.(5). Therefore, the clear distance between bolts and the distance from the center of any bolt to the end of the connection member toward which the pressure of the bolt is directed shall not be less than 1 1/2 d nor less than e_{min} determined by Eq. (20).

Because most of the previous studies on the longitudinal shear strength of bolted connections have been performed on specimens that have been torqued to the same specified values, it appears that additional tests in which various amounts of torques are used should be conducted on bolted connections. In addition, connections with bolts pretensioned to the values specified by the Research Council on Riveted and Bolted Structural Joints (Table 15) should be investigated.

Further study is needed for bolted connections without washers to conform to Eq. (19).

D. Tensile Strength

1. General

In the design of hot-rolled steel shapes, it is a general practice to assume that the average stress on the net section of a tension member can reach the yield point of steel. This assumption is based on the fact that the effect of stress concentrations at bolt holes is rendered insignificant by plastic stress redistribution. From the results of the Cornell investigation, Winter[3,4] concluded that for test specimens failed by tearing in the net section the complete disregard of stress concentrations is not warranted for bolted connections in cold-formed steel construction. He pointed out that the d/s ratio has a decided influence on the failure stress. For the condition of one bolt in the line of stress, the tension stress at failure can be represented by

$$\sigma_{net} = (0.10 + 3.0\ d/s)\ F_u \leq F_u. \tag{21}$$

The above equation indicates that when the d/s ratio exceeds 0.30 plastic redistribution eliminates completely the effect of stress concentration in the same manner as hot-rolled sections.

A recent study conducted at Cornell by Popowich[5] has shown that the sharp stress concentration can be much relieved when more than one bolt in line is used. As a result, the failure in the net section for two-bolt and three-bolt tests occurred at a much higher stress than for single bolt connections. As a general design criterion, the following formula has been developed to predict the failure stress in the net section for single and multibolt connections:

$$\sigma_{net} = [1 - 0.9\ r + 3\ r\ (d/s)]\ F_u \leq F_u \tag{22}$$

where σ_{net} = failure stress in net section

r = force transmitted by the bolt or bolts at the section considered, divided by the force in the member at that section

From Eq. (22), it can be seen that when r is equal to 1.0 the same equation (Eq. (21)) developed by Winter can be obtained.

The present AISI[1] Specification states that "the tension stress on the net section of a bolted connection shall not exceed 0.6 F_y nor shall it exceed

$$(1.0 - 0.9\ r + 3\ rd/s)\ 0.6\ F_y \qquad (23)$$

It should be noted that Eqs. (21) to (23) apply to both single and double shear connections. Equations (21) to (23) are based on single shear tests only. It appears that additional tests may be needed for double shear, multibolt connections so that these two equations can be verified for both types of connections.

2. Effect of Ductility

The effect of the ductility of steel on the structural strength of bolted connections was discussed in Section II.A. Modified equations were given for the determination of the bearing stress and the longitudinal shear strength of steel sheets. Based on his recent study[6], Dhalla concluded that the ultimate tensile strength is not affected by the ductility of the steel.

Equations (21) and (22) are based on the specified tensile strength to yield point ratios equal to or greater than 1.35. When the ratio is less than 1.35, the present AISI Specification requires that a stress equal to the specified minimum tensile strength divided by 1.35 be used instead of F_y in the design formulas.

From the tests conducted at Cornell, Winter[15] concluded that the load at which tearing occurs correlates better with the tensile strength than with the yield point of the steel. By letting $F_y = F_u/1.35$, Eq. (23) can be written in terms of the tensile strength of the steel as follows:

$$(1.0 - 0.9\ r + 3\ rd/s)\ 0.44\ F_u. \qquad (24)$$

Equation (24) allows one to determine the allowable tensile stress on the net section of a bolted connection on the basis of the ultimate strength of the steel sheets.

3. Effect of d/s Ratio

As mentioned in Section II.D.1, the tensile strength of a bolted connection is dependent upon the d/s ratio, F_u and the number of bolts in the line of the load and can be predicted by Eq. (22). Even though some of Winter's tests with low d/s ratios showed the net stresses in excess of F_u, the ultimate tensile strength of steel sheets has been regarded as an upper limit for Eq. (22).

When a bolted connection is composed of only one bolt in the line of stress, Eq. (22) can be simplified to Eq. (21). The results of the Cornell tests for both single and double shear connections that failed by tearing across the net section are given in Tables 8 through 12. Figures 17 and 18 are plots of σ_{net}/F_u vs. d/s for single shear connections with high- and low-ductility steels, respecitvely. From Fig. 19, which is a combination of Figs. 17 and 18, it can be seen that Eq. (21) gives a good prediction of the tensile strength of single shear connections composed of high- and low-ductility steels. It can be concluded that the ductility has little effect on the tensile strength of a single shear connection.

Figures 20 and 21 are plots of σ_{net}/F_u vs. d/s for double shear connections with high- and low-ductility steels, respectively. If Figs. 20 and 21 are combined as shown in Fig. 22, it can be seen that for double shear connections Eq. (21) gives a conservative prediction of the test results. Again it can be concluded that the ductility has little effect on the tensile strength of a bolted connection.

Figure 23 is a plot of σ_{net}/F_u vs. d/s for multibolt connections based on the data obtained by Popowich[5]. Details of the results are given in Table 12. Equation (22) is shown for r = 1, 1/2, and 1/3. It can be seen that when $r = 1/2$ and $1/3$, Eq. (22) gives a conservative prediction of the test results. As mentioned earlier, the data shown in Fig. 22 are for single shear connections only. Additional tests may be needed for double shear connections that are governed by tensile strength.

4. Effect of d/t Ratio

The present AISI equation for determining the tensile strength of a bolted connection is dependent upon the dimensional parameters d and s. An investigation, similar to studies of bearing and shear strengths made in Sections II.B.3 and II.C.3, was made on the effect of the d/t ratio on the tensile strength.

Test data obtained from the Cornell tests have been studied and are presented in Tables 8 through 12. In order to determine the effect of the d/t ratio on the tensile strength, the nondimensional ratios of $(\sigma_{net})_{cal}/(\sigma_n)_{test}$ are plotted against d/t in Figs. 24 to 26 for the same d/s ratios. These data are separated according to single and double shear connections that have multibolt conditions. From these figures, it can be seen that the d/t ratio has no significant effect on the tensile strength of bolted connections. It appears that a further study of the combination of d/t greater than 10.0 and d/s less than 0.15 is desirable.

5. Effect of Washers

The present equation for the tensile strength of a bolted connection is based on tests in which washers were used under both the heads and nuts. Chong and Matlock, who studied the bolted connections without washers, developed the following equation for the tensile strength in net section:

$$\sigma_{net} = [0.6 - 0.66\,r + 2.92\,(d/s)]\,F_u \leq F_u. \qquad (25)$$

The above equation indicates that the tensile strength of the net section depends on the parameters "r" and "d/s". However, Eq. (22) developed by Winter for bolted connections with washers depends on the parameters r and rd/s. For this reason, further study will be made in this project to determine the appropriate parameters to be used in the prediction of tensile strength.

6. Tentative Recommendations

The preceding discussion indicates that Eq. (22) may be used for the determination of the tensile strength of a bolted connection. This equation uses the tensile strength of the steel rather than the yield point.

As a result of the different parameters involved in Eqs. (22) and (25) for connections with and without washers, respectively, further research will be conducted in this area.

E. Shearing Strength of Bolts

The shearing strength of bolts depends on the mechanical properties of the bolt, the number of shear planes, joint length, pretension in bolts, surface condition between connected parts, hole clearance, and the type of loading condition. Numerous double and single shear tests have been conducted at Cornell University to study the type of failure in which shearing of the bolt for light gage steel bolted connections occurs. On the basis of an investigation of the shear strength of connections for which ordinary bolts were used, Winter concluded that the maximum shear capacity of bolts correlates better with the tensile strength than with the yield point of the bolt material. The shear stress at failure on the root area can be determined by the following equation for single shear connections:

$$\tau_b = 0.72\ F_{u_b}. \tag{26}$$

For double shear connections, the shear stress is

$$\tau_b = 0.62\ F_{u_b} \tag{27}$$

where F_{u_b} is the ultimate tensile strength of the bolt. The higher shear stress for the single shear tests is believed to be due to two reasons: (1) Because of the bending and warping of the sheet, the bolt develops an oblique position, which results in a decrease of the shear stress on the normal section, with a simultaneous occurrence of tension. Because steel is stronger in tension than in shear, there is an increase in bolt resistance. (2) Although the failures of double shear tests occur in two parallel shear planes, the planes are so close to each other that some mutual weakening is conceivable for light gage steel.

Because shear failures of bolts are more sudden than those for sheets, Winter has suggested the following conservative equation for both single and double shear connections:

$$\tau_b = 0.60\ F_{u_b}. \tag{28}$$

Additional tests were also conducted at Cornell on light gage steel connections with high-strength bolts. From this study, Winter[4] concluded that the equations developed from the corrections with ordinary bolts also apply to connections for which high-strength bolts are used. By using high strength bolts, the required number of bolts can be reduced, and the slip at design loads can be eliminated.

In the AISI Specification, the allowable shear stress on the gross sectional area of the bolt cannot exceed the following values:

1) For ASTM A307 bolts,

$$F_v = 10 \text{ ksi}. \tag{29}$$

2) For ASTM A325 bolts,

when threading is excluded from shear planes,

$$F_v = 22 \text{ ski*}; \tag{30}$$

and when threading is not excluded from shear planes,

$$F_v = 15 \text{ ksi*} \tag{31}$$

where F_v = the allowable shear stress.

These values are the same as the AISC Specification. It should be noted that the allowable shear stresses included in the AISI Specification are for the bearing-type connections only. No provisions are included for the design of friction-type connections.

In their recent study, Chong and Matlock[7] concluded that for bolted connections without washers the allowable shear stress on the gross cross-sectional area of bolts is the same as that for the connections using washers.

F. Other Specifications

The specifications being used in Canada and several European countries for the design of bolted connections have been briefly reviewed. The following is a comparison of some of the design criteria:

1. Minimum Edge Distance in Line of Stress

Concerning the minimum edge distance for a bolted connection, the Canadian Standard[16] specifies that

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*Higher allowable shear stresses on bolts have been proposed by subcommittee 3 of the AISI Advisory Group on Specification[22]

$$e \geq 1.5\ d \tag{32}$$

and
$$e \geq \frac{P}{F^* t} \tag{33}$$

where F^* is the design stress based on working stress design. In addition, the limit states design may be used. The above two equations are practically identical with the AISI design provisions except that in Eq. (33) the design stress F^* shall be equal to the basic design stress F or $(F_u/r.35\ F_y)$ F, whichever is smaller.

The British[17] and French[19] specifications allow the same requirements for the edge distance for cold-formed steel as those used for hot-rolled bolted connections.

The edge distance of bolted connections in thin-walled steel structures is also one of the requirements in the Swedish recommendations.[18]

Based on the edge conditions, it requires that for unstiffened edges, the edge distance, e, is

$$1.5\ d \leq e \leq 2.5\ d.$$

For a stiffened edge, the edge distance should not exceed five times the nominal diameter of the bolt.

The above discussion indicates that in the Swedish recommendations, the minimum requirement for the end distance is similar to the AISI Specification with additional limitations.

2. Allowable Bearing Stress

With regard to the design criteria for the bearing strength of a bolted connection, the Canadian Standard is similar to the AISI Specification. The allowable bearing stress permitted by the British Standard is 0.8 F_y, which is considerably smaller than that permitted by AISI. In the French recommendation, the allowable bearing stress is determined as four times the allowable tensile strength of the steel sheets. The allowable bearing stress, permitted by the Swedish recommendations, depends on the bolted joint class, bolt quality, number of shear planes, stress grade of steel sheets, and loading conditions. For typical load cases, the allowable bearing stress varies from 0.55 F_y to 0.72 F_y.

3. Allowable Tension in Net Section

A similar allowable tension stress is being used in Canada and Sweden as that specified by the current AISI design specification. In Great Britain and France, the same allowable tension stress is used for cold-formed steel members and hot-rolled shapes.

4. Allowable Shear Stress on Bolts

The Canadian Standard permits the same allowable shear stress for A307 bolts as the AISI Specification and slightly higher values for high strength bolts. In Great Britian and France, the same allowable shear stresses are used for thin-walled, cold-formed steel members and hot-rolled shapes.

III. SUMMARY AND CONCLUSIONS

In the United States and some other countries, the design of bolted connections in cold-formed steel structures is based on the AISI Specification for the Design of Cold-Formed Steel Structural Members. The first phase of this investigation has been conducted for the purposes of reviewing the available test data on bolted connections and studying the needed additional design criteria for the 1968 Edition of the AISI Specification concerning minimum edge distance, allowable tension on net section, allowable bearing stress in bolted connections, and allowable shear stress on bolts.

Based on the analysis of available test data, it was found that the spread between the ultimate tensile strength and yield point of the steel sheets (i.e., F_u/F_y ratio) affects considerably the bearing strength of bolted connections and the shear strength of steel sheets particularly when $F_u/F_y < 1.35$. The tests made at Cornell have shown that the decrease of F_u/F_y ratio results in a reduction of bearing strength of the connection. However, the tensile strength of the connection is not affected significantly by the F_u/F_y ratio. In order to consider the effect of F_u/F_y ratio, the present AISI design formulas for the allowable bearing stress and the minimum edge distance can be modified simply by using an equivalent yield point "C_2F_y" to replace F_y in the 1968 Edition of the Specification.

A study of the difference between single shear and double shear conditions indicates that the double shear condition can provide a slightly higher bearing strength than the single shear condition. For the sake of simplicity, no modification of the present design criteria appears to be necessary.

The effect of the d/t ratio on the strengths of bolted connections was also investigated. It was found that in general the d/t ratio has little or no effect on the bearing strength of bolted connections, the longitudinal shear strength of steel sheets, and the tensile strength of net section.

The test data published by Chong and Matlock on bolted connections without washers show that the washers play an important role in the bearing and tensile strengths of connections. These data were reviewed and analyzed in the text. Design formulas are also proposed in this report.

The second phase of the project will include analytical and experimental investigations concerning the effect of torque on bearing strength, tensile strength of net section, bearing strength of thin sheets, effect of d/t, and effect of washers. Details of the planned work are discussed in Article IV of the report.

IV. FUTURE STUDY

On the basis of the research proposal submitted to American Iron and Steel Institute in 1975[20] and the analysis of available test data on bolted connections conducted in this investigation, the following future studies are planned to be carried out in the second phase of this investigation.

1. Effect of Torque on Bearing Strength of Bolted Connections

In the study of the effect of torque on bearing strength, the following parameters will be considered:

A. Torque or initial tension in bolts

1) No torque

2) Same torque as used in the Cornell tests (See Tables 13 and 14)

3) Same initial bolt tension as specified by the Research Council on Riveted and Bolted Structural Joints (See Table 15)

B. Thickness of steel sheets

t = 0.024, 0.06, and 0.105 in.

C. Diameter and material of bolts

d = 1/4 to 3/4 in.

Use A307 bolts and high strength bolts (A325 bolts) as appropriate.

D. Ratio of e/d

e/d = 1.5, 2.5, 3.5, and 4.5

E. Washers

Tests will be conducted with and without washers

F. Ratio of F_u/F_y

$F_u/F_y = 1.1$ to 1.80

This means that any steel sheets or strip having an F_u/F_y ratio within the above range can be used for the tests.

G. Number of rows perpendicular and parallel to the line of stress

Use one-bolt condition ($r = 1.0$)

H. Use single shear condition only. It is assumed that the effect of torque is approximately the same for single and double shear conditions.

I. The ratios of d/s and d/t are not specified for this portion of the study. They will be determined as required by the tensile strength of the connection and other practical considerations.

With regard to the pretension in bolts indicated in Item A.(c), it appears that new methods of measuring the pretension need to be developed.

The findings to be obtained from this portion of the investigation may also be used for the longitudinal shear strength of steel sheets.

2. Tensile Strength of Net Section

Because the purpose of studying tensile strength was to reevaluate the parameters to be used for determining the allowable tensile stress in bolted connection design, the following variables will be considered in the analytical and experimental investigations:

A. Torque or initial tension in bolts

Use initial tension in bolts as specified by the Research Council if new methods for measuring initial tension are available. Otherwise, the torque used for Cornell tests will be used for this portion of study.

B. Thickness of steel sheets

$t = 0.024$, 0.06, and 0.105 in.

C. Diameter and material of bolts

$d = 1/4$ to 3/4 in.

Use A307 and A325 bolts

D. Ratio of e/d

$e/d \geq 3.5$

E. Washers

Tests will be conducted with and without washers

F. Ratio of F_u/F_y

The F_u/F_y ratio of the steel used will be within the range of 1.10 to 1.80.

G. Number of rows perpendicular and parallel to the line of stress

$r = 1$, 1/2, and 1/3 (use one, two, and three rows parallel to the line of stress) Few tests may be conducted for multiple rows both perpendicular and parallel to the line of stress.

H. Use both single shear and double shear conditions.

I. Ratio of d/s

$d/s = 0.1$, 0.2, 0.3, and 0.4

3. Other Subjects

Other future studies will be planned at a later date as necessary.

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APPENDICES

APPENDIX A

Notation

e = edge distance

d = diameter of the bolt

s = spacing of bolts normal to direction of force; for single bolt at section, it is full width of connected sheet

t = thickness of connected sheet

F_u = ultimate tensile stress of sheet

F_y = yield stress of material

C_2 = ductility factor

σ_b = ultimate bearing stress

F_p = allowable bearing stress

P_u = ultimate failure load

τ_s = nominal shear stress at failure

σ_{net} = tension stress at failure of bolted connection

τ_b = shear stress at failure of bolt

F_{u_b} = ultimate tensile strength of bolt

APPENDIX B

Tables

Table 1. Dimensions and Results of Bolted Connections With Washers-Both High and Low Ductility Steels [6]

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	P_{ult} (kips)	F_y (ksi)	F_u (ksi)	σ_b (ksi)	σ_b/F_y	C_2	σ_b/C_2F_y	Failure* Type
16FAX-L14	1/2	0.062	1.25	2.5	2.5	8.06	3.20	30.1	45.9	103.20	3.43	1.000	3.43	I & II
16FAXL15			1.75		3.5		5.10			164.50	5.47	1.000	5.47	II & III
16FAXL16			1.75				4.80			154.84	5.14	1.000	5.14	II & III
16FAXL17				5.0			4.28			138.10	4.60	1.000	4.60	II
12FAXL19		0.106	1.25	2.5	2.5	4.72	6.44	28.1	44.1	121.51	4.32	1.000	4.32	II & 1
12FAXL20			1.75		3.5		8.25			155.66	5.54	1.000	5.54	II & III
12FAXL21				5.0			9.55			180.20	6.41	1.000	6.41	II
1610X-L19		0.062	1.50	2.5	3.0	8.06	6.68	78.4	81.5	215.50	2.75	0.643	4.28	II
1610X-L20			1.75	2.5	3.5		7.14			230.30	2.94	0.643	4.57	II
1610X-L21				2.0			5.04			162.60	2.07	0.643	3.22	II
1610XL30			1.40	5.0	2.8		4.86			156.77	2.00	0.643	3.11	II
1615XL23			1.50	2.5	3.0		5.92	45.4	54.7	190.97	4.21	0.793	5.31	II & III
1615XL24			1.75	2.5	3.5		5.59	45.4	54.7	180.32	3.97	0.793	5.01	II
1615XL25				2.0			4.34			140.00	3.08	0.793	3.89	II
1615XL31			1.40	5.0	2.8		4.32			139.40	3.07	0.793	3.87	II
1625X-L27			1.50	2.5	3.0		4.94	38.5	49.1	159.35	4.14	0.894	4.63	II & III
1625X-L28			1.75		3.5		5.17			166.77	4.33	0.894	4.84	II & III
1625X-L29				2.0			4.20			135.50	3.52	0.894	3.94	II
1625X-L32			1.40	5.0	2.8		4.62			149.00	3.87	0.894	4.33	II
1210X-L23		0.106	1.50	2.5	3.0	4.72	11.74	70.1	72.8	221.51	3.16	0.643	4.91	II
1210X-L24			1.75		3.5		11.62			219.25	3.13	0.643	4.87	II
1210X-L25				2.0			11.86			223.77	3.20	0.643	4.98	II & III
1210X-L36			1.40	5.0	2.8		10.88			205.30	2.93	0.643	4.56	II
1215X-L27			1.50	2.5	3.0		11.03	65.2	69.3	208.11	3.20	0.643	4.98	II
1215X-L28			1.75	2.5	3.5		11.32			213.60	3.28	0.643	5.10	II
1215XL29				2.0			10.74			202.60	3.11	0.643	4.84	III & II
1215XL35			1.40	5.0	2.8		10.26			193.58	2.97	0.643	4.62	II
1225XL31			1.50	2.5	3.0		8.76	36.6	50.0	165.30	4.52	1.000	4.52	II & III
1225XL-32			1.75		3.5		8.81			166.23	4.54	1.000	4.54	II & III
1225XL33				2.0			7.92			149.43	4.08	1.000	4.08	II & III
1225XL34			1.40	5.0	2.8		8.84			166.79	4.56	1.000	4.56	II

*The types of failure are defined as follows:

I--Longitudinal shearing of the steel sheets
II--Bearing failure between steel sheet and bolt
III--Transverse tension tearing failure
IV--Shearing of the bolt

Table 2. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Single Shear)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
20A41SS	1/4	0.036	1.125	4.0	4.5	6.94	32.11	41.83	208.29	0.933	6.96	146.8	0.704	II	9
14A43SS	1/2	0.08	2.25			6.25	29.81	43.40	177.5	1.0	5.95	146.1	0.823	II	9
10E36SS	1.0	0.143	3.5		3.5	6.98	59.47	76.84	172.25	0.918	3.16	267.5	1.55	II	10
12Y-L7	1/2	0.106	1.75	4.0	3.5	4.72	72.4	72.8	239.0	0.643	5.13	228.14	0.952	II & I	6
12Y-L8	3/8		1.5	2.53	4.0	3.54			245.0		5.26		0.932	II	
12Y-L9	1/2		1.75	3.41	3.5	4.72			267.0		5.74		0.855	II	
12Y-L11	3/8		1.49	2.0	4.0	3.54			216.0		4.63		1.05	II & I	
12Y-L12	1/2		1.75	2.66	3.5	4.72			211.0		4.53		1.09	II & III	
12Y-L15	3/8		1.5	1.52	4.0	3.54			194.0		4.17		1.17	II & III	
12Y-L16	1/2		1.75	2.04	3.5	4.72			211.0		4.53		1.08	II	
12Y-L18	3/4		2.65	3.04	3.53	7.08			153.0		3.28		1.49	II	
7Y-L6	3/4	0.183	3.75	3.75	5.0	4.10	83.1	83.8	307.0		5.74	262.0	0.855	II & III	
20ZT12	3/16	0.038	0.66	2.08	3.5	4.93	99.4	99.8	260.0		4.07	313.2	1.20	II	
16FAX-L16	1/2	0.062	1.75	2.5	3.5	8.06	30.1	45.9	152.2	1.0	5.06	147.5	0.969	II & III	
SS2	7/8	0.116	3.06	8.0		7.54	35.49	49.44	158.57		4.47	173.9	1.1	II	14
SS2-1	7/8		3.06						121.92		3.44		1.43	II	
SS3	7/8		4.4		5.0				149.29		4.21		1.16	II	
SS5	1.0		3.5		3.5	8.62			133.84		3.77		1.3	II	
SS5-1	1.0		3.5		3.5	8.7			117.61		3.31		1.48	II	
SS6	1.0		3.5		5.0	8.62			132.25		3.73		1.31	II	
SS8	7/8	0.181	3.06		3.5	4.83	38.1	62.08	208.37		5.47	186.7	0.896	II	
SS8-1	7/8	0.181	3.06	8.0	3.5	4.83	38.1	62.08	156.59	1.0	4.11	186.7	1.2	II	
SS9	7/8	0.185	4.375	8.0	5.0	4.73			202.32		5.31		0.923	II	
SS11	1.0	0.184	3.5		3.5	5.43			200.0		5.25		0.933	II	
SS11-1		0.184	3.5		3.5				164.67		4.32		1.133	II	
SS12		0.184	5.0		5.0				191.85		5.04		0.973	II	
SS14		0.261	3.5		3.5	3.83	45.07	67.54	216.86		4.81	220.8	0.843	II	
SS14-1		0.259	3.5		3.5	3.86			178.96		3.91		0.81	II	
SS15		0.255	5.0		5.0	3.92			217.65		4.83		0.986	II	

Table 2. (con't)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
--	1/2	0.037	2.0	4.0	4.0	13.5	53.5	58.9	200.0	0.644	5.81	168.86	0.844	II	7
--	1/2	0.037	2.0	4.03	4.0	13.5	53.5	58.9	197.8	0.644	5.75	168.86	0.854	II	
--	5/16	0.037	2.06	4.06	6.6	8.45	53.5	58.9	183.4	0.644	5.33	168.86	0.921	II	
--	5/16	0.037	2.04	4.06	6.53	8.45	53.5	58.9	190.4	0.644	5.53	168.86	0.887	II	
--	1/2	0.037	2.5	4.0	5.0	13.5	53.5	58.9	207.6	0.644	6.02	168.86	0.813	II	
--	1/2	0.037	2.0	4.0	4.0	13.5	53.5	58.9	214.6	0.644	6.23	168.86	0.787	II & I	
--	1/2	0.051	2.03	4.0	4.06	9.8	40.6	50.1	158.8	0.835	4.68	166.11	1.05	II & I	
--	1/2	0.051	2.03	4.0	4.06	9.8	40.6	50.1	165.9	0.835	4.91	166.11	1.0	II & I	
--**	1/2	0.061	1.94	2.03	3.88	8.2	50.5	74.1	201.7	1.0	4.0	247.45	1.23	II	

*$(\sigma_b)_{cal} = 4.9\ C_2Fy$

Mean = 1.04

Standard Deviation = 0.21

**Two bolts perpendicular to line of stress

See Table 1 for the definition of type of failure

Table 1. Dimensions and Results of Bolted Connections With Washers-Both High and Low Ductility Steels [6]

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	P_{ult} (kips)	F_y (ksi)	F_u (ksi)	σ_b (ksi)	σ_b/F_y	C_2	σ_b/C_2F_y	Failure* Type
106FAX-L14	1/2	0.062	1.25	2.5	2.5	8.06	3.20	30.1	45.9	103.20	3.43	1.000	3.43	I & II
106FAXL15			1.75		3.5		5.10			164.50	5.47	1.000	5.47	II & III
106FAXL16			1.75				4.80			154.84	5.14	1.000	5.14	II & III
106FAXL17				5.0			4.28			138.10	4.60	1.000	4.60	II
127FAXL19		0.106	1.25	2.5	2.5	4.72	6.44	28.1	44.1	121.51	4.32	1.000	4.32	II & I
127FAXL20			1.75		3.5		8.25			155.66	5.54	1.000	5.54	II & III
127FAXL21				5.0			9.55			180.20	6.41	1.000	6.41	II
1610SX-L19		0.062	1.50	2.5	3.0	8.06	6.68	78.4	81.5	215.50	2.75	0.643	4.28	II
1610SX-L20			1.75	2.5	3.5		7.14			230.30	2.94	0.643	4.57	II
1610SX-L21				2.0			5.04			162.60	2.07	0.643	3.22	II
1610SXL30			1.40	5.0	2.8		4.86			156.77	2.00	0.643	3.11	II
1615SXL23			1.50	2.5	3.0		5.92	45.4	54.7	190.97	4.21	0.793	5.31	II & III
1615SXL24			1.75	2.5	3.5		5.59	45.4	54.7	180.32	3.97	0.793	5.01	II
1615SXL25				2.0			4.34			140.00	3.08	0.793	3.89	II
1615SXL31			1.40	5.0	2.8		4.32			139.40	3.07	0.793	3.87	II
1625SX-L27			1.50	2.5	3.0		4.94	38.5	49.1	159.35	4.14	0.894	4.63	II & III
1625SX-L28			1.75		3.5		5.17			166.77	4.33	0.894	4.84	II & III
1625SX-L29				2.0			4.20			135.50	3.52	0.894	3.94	II
1625SX-L32			1.40	5.0	2.8		4.62			149.00	3.87	0.894	4.33	II
1210SX-L23		0.106	1.50	2.5	3.0	4.72	11.74	70.1	72.8	221.51	3.16	0.643	4.91	II
1210SX-L24			1.75		3.5		11.62			219.25	3.13	0.643	4.87	II
1210SX-L25				2.0			11.86			223.77	3.20	0.643	4.98	II & III
1210SX-L36			1.40	5.0	2.8		10.88			205.30	2.93	0.643	4.56	II
1215SX-L27			1.50	2.5	3.0		11.03	65.2	69.3	208.11	3.20	0.643	4.98	II
1215SX-L28			1.75	2.5	3.5		11.32			213.60	3.28	0.643	5.10	II
1215SXL29				2.0			10.74			202.60	3.11	0.643	4.84	III & II
1215SXL35			1.40	5.0	2.8		10.26			193.58	2.97	0.643	4.62	II
1225SXL31			1.50	2.5	3.0		8.76	36.6	50.2	165.30	4.52	1.000	4.52	II & III
1225SXL-32			1.75		3.5		8.81			166.23	4.54	1.000	4.54	II & III
1225SXL33				2.0			7.92			149.43	4.08	1.000	4.08	II & III
1225SXL34			1.40	5.0	2.8		8.84			166.79	4.56	1.000	4.56	II

*The types of failure are defined as follows:

I--Longitudinal shearing of the steel sheets
II--Bearing failure between steel sheet and bolt
III--Transverse tension tearing failure
IV--Shearing of the bolt

Table 1. Dimensions and Results of Bolted Connections With Washers-Both High and Low Ductility Steels [6]

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	P_{ult} (kips)	F_y (ksi)	F_u (ksi)	σ_b (ksi)	σ_b/F_y	C_2	σ_b/C_2F_y	Failure* Type
16FAX-L14	1/2	0.062	1.25	2.5	2.5	8.06	3.20	30.1	45.9	103.20	3.43	1.000	3.43	I & II
16FAXL15			1.75		3.5		5.10			164.50	5.47	1.000	5.47	II & III
16FAXL16			1.75				4.80			154.84	5.14	1.000	5.14	II & III
16FAXL17				5.0			4.28			138.10	4.60	1.000	4.60	II
12FAXL19		0.106	1.25	2.5	2.5	4.72	6.44	28.1	44.1	121.51	4.32	1.000	4.32	II & I
12FAXL20			1.75		3.5		8.25			155.66	5.54	1.000	5.54	II & III
12FAXL21				5.0			9.55			180.20	6.41	1.000	6.41	II
1610X-L19		0.062	1.50	2.5	3.0	8.06	6.68	78.4	81.5	215.50	2.75	0.643	4.28	II
1610X-L20			1.75	2.5	3.5		7.14			230.30	2.94	0.643	4.57	II
1610X-L21				2.0			5.04			162.60	2.07	0.643	3.22	II
1610XL30			1.40	5.0	2.8		4.86			156.77	2.00	0.643	3.11	II
1615XL23			1.50	2.5	3.0		5.92	45.4	54.7	190.97	4.21	0.793	5.31	II & III
1615XL24			1.75	2.5	3.5		5.59	45.4	54.7	180.32	3.97	0.793	5.01	II
1615XL25				2.0			4.34			140.00	3.08	0.793	3.89	II
1615XL31			1.40	5.0	2.8		4.32			139.40	3.07	0.793	3.87	II
1625X-L27			1.50	2.5	3.0		4.94	38.5	49.1	159.35	4.14	0.894	4.63	II & III
1625X-L28			1.75		3.5		5.17			166.77	4.33	0.894	4.84	II & III
1625X-L29				2.0			4.20			135.50	3.52	0.894	3.94	II
1625X-L32			1.40	5.0	2.8		4.62			149.00	3.87	0.894	4.33	II
1210X-L23		0.106	1.50	2.5	3.0	4.72	11.74	70.1	72.8	221.51	3.16	0.643	4.91	II
1210X-L24			1.75		3.5		11.62			219.25	3.13	0.643	4.87	II
1210X-L25				2.0			11.86			223.77	3.20	0.643	4.98	II & III
1210X-L36			1.40	5.0	2.8		10.88			205.30	2.93	0.643	4.56	II
1215X-L27			1.50	2.5	3.0		11.03	65.2	69.3	208.11	3.20	0.643	4.98	II
1215X-L28			1.75	2.5	3.5		11.32			213.60	3.28	0.643	5.10	II
1215XL29				2.0			10.74			202.60	3.11	0.643	4.84	III & II
1215XL35			1.40	5.0	2.8		10.26			193.58	2.97	0.643	4.62	II
1225XL31			1.50	2.5	3.0		8.76	36.6	50.0	165.30	4.52	1.000	4.52	II & III
1225XL-32			1.75		3.5		8.81			166.23	4.54	1.000	4.54	II & III
1225XL33				2.0			7.92			149.43	4.08	1.000	4.08	II & III
1225XL34			1.40	5.0	2.8		8.84			166.79	4.56	1.000	4.56	II

*The types of failure are defined as follows:

I--Longitudinal shearing of the steel sheets
II--Bearing failure between steel sheet and bolt
III--Transverse tension tearing failure
IV--Shearing of the bolt

Table 3. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Double Shear)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
20A41DS	1/4	0.036	1.125	4.0	4.5	6.94	32.11	41.85	206.32	0.934	6.89	147.0	0.713	II	9
16C403DS	1/2	0.0591	2.0		4.0	8.46	31.95	43.95	224.03	1.0	7.01	156.6	0.7	II	9
16C503DS	1/2	0.0591	2.5		5.0	8.46	31.95	43.95	243.66	1.0	7.63	156.6	0.643	II	9
14E35DS	3/4	0.0783	2.625		3.5	9.58	54.44	70.4	242.20	0.919	4.84	245.2	1.011	I & II	10
10E36DS	1.0	0.143	3.5		3.5	6.98	59.5	71.85	199.35	0.797	4.2	232.4	1.16	II	10
10E46DS	1.0	0.143	4.5		4.5	6.98	59.5	71.85	201.5	0.797	4.2	232.4	1.16	II	10
20Z-L8	3/16	0.038	.66	2.08	3.52	4.93	75.7	81.7	206.0	0.643	4.23	238.5	1.16	II & I	6
1205XL7	3/4	0.106	2.63	3.75	3.5	7.08	81.6	81.6	252.0		4.81	257.1	1.02	II & I	
1205XL8	3/4		2.63	3.0	3.5	7.08			236.0		4.49		1.08	II & III	
1205XL9	7/8		3.06	3.5		8.25			242.0		4.62		1.06	II & III	
7Y-L32	5/8	0.183	2.19	2.98		3.42	82.6	82.6	247.0		4.65	258.3	1.05	II & I	
16FAXL15	1/2	0.062	1.75	2.5		8.06	30.1	45.9	161.8	1.0	5.38	147.5	0.912	II & III	
16FAXL17	1/2			5.0					136.0		4.52		1.08	II	
12FAX-L20	1/2	0.106		2.5		4.72	28.1	44.1	159.2		5.67	137.7	0.865	II & III	
12FAX-L21	1/2	0.106		5.0		4.72			178.4		6.35		0.772	II	
DS1-1	7/8	0.116	3.06	8.0	3.5	7.54	35.49	49.44	161.58	1.0	4.55	173.9	1.08	II	14
DS1-2		0.116	3.06						148.77		4.19		1.17		
DS2-1	1.0	0.115	3.5			8.7			139.13		3.92		1.25		
DS2-2		0.116	3.5			8.62			143.10		4.03		1.22		
DS3-1	7/8	0.181	3.06			4.83	38.1	62.08	209.94		5.51	186.7	0.889		
DS3-2		0.180	3.06			4.86			196.14		5.15		0.952		
DS4-1	1.0	0.182	3.5			5.49			229.12		6.01		0.815		
DS4-2		0.181				5.52			223.76		5.87		0.834		
DS5-1		0.259				3.86	45.07	67.54	221.62		4.92	220.8	0.996		
DS5-2		0.26				3.85	45.07		222.31		4.93		0.993		

$*(\sigma_b)_{cal} = 4.9\ C_2Fy$

Mean = 0.930

See Table 1 for definition of type of failure

Standard Deviation = 0.170

Table 4. Dimensions and Results of Bolted Connections without Washers-Bearing Strength Study [7] e/d > 2.5

Gage of Steel	Connection* Type	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^{**}_{cal}$ (ksi)	$(\sigma_b)^{***}_{cal}$ (ksi)	$\frac{(\sigma_b)^{**}_{cal}}{(\sigma_b)_{test}}$	$\frac{(\sigma_b)^{***}_{cal}}{(\sigma_b)_{test}}$	Failure Type
20	1	1/2	0.037	2.06	4.06	4.06	13.5	53.5	58.9	133.0	0.644	3.9	168.86	120.6	1.27	0.91	I & II
20	1	5/16	0.037	2.04	4.03	6.53	8.45			158.4		4.6			1.07	0.76	II
20	1	5/16	0.037	2.06	4.12	6.6	8.45			138.4		4.04			1.22	0.87	I & II
20	1	1/2	0.037	2.5	4.0	5.0	13.5			122.2		3.55			1.38	0.987	II
20	1	1/2	0.037	2.5	4.0	5.0	13.5			125.0		3.63			1.35	0.965	II
17	1	1/2	0.051	2.06	4.03	4.12	9.8	40.6	50.1	113.3	0.835	3.34	166.11	118.65	1.47	1.05	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.8			117.0		3.45			1.42	1.01	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.8			115.3		3.4			1.11	1.03	I & II
17	3	5/16	0.051	2.05	1.35	6.56	6.13			109.6		3.23			1.52	1.08	II
17	3	5/16	0.051	2.07	1.35	6.62	6.13			112.7		3.33			1.47	1.05	II
17	2	1/2	0.051	1.97	2.02	3.94	9.8			109.2		3.22			1.52	1.09	I & II
16	2	1/2	0.061	1.97	2.0	3.94	8.2	50.5	74.1	147.2	1.0	2.91	247.45	176.75	1.68	1.2	II
14	1	3/4	0.079	3.0	4.0	4.0	9.5	52.8	65.9	145.1	0.855	3.21	221.2	158.0	1.52	1.09	I & II
14	1	3/4	0.079	3.01	4.0	4.0	9.5			137.6		3.05			1.61	1.15	I & II
14	1	3/4	0.079	3.0	4.0	4.0	9.5			154.8		3.43			1.43	1.02	I & II
12	1	3/4	0.104	3.03	4.06	4.04	7.2	59.3	70.6	160.3	0.772	3.5	224.34	160.23	1.4	1.00	I & II
20	1	1/2	0.037	1.5	4.0	3.0	13.5	53.5	58.9	130.3	0.644	3.77	168.86	120.6	1.3	0.926	I
20	1	1/2	0.037	1.5	3.06	3.0	13.5			123.8		3.69			1.36	0.974	I
20	1	1/2	0.037	1.5	3.03	3.0	13.5			122.2		3.54			1.38	0.987	I
17	1	1/2	0.051	1.5	2.02	3.0	9.8	40.6	50.1	112.2	0.835	3.31	166.11	118.65	1.48	1.06	I
17	1	1/2	0.051	1.44	2.02	2.88	9.8			113.7		3.35	166.11	118.65	1.46	0.04	I
20	1	1/2	0.037	2.03	4.06	4.06	13.5	53.5	58.9	120.5	0.644	3.5	168.86	120.6	1.4	1.00	I
20	1	1/2	0.037	2.07	4.06	4.14	13.5			131.4		3.81			1.28	0.918	I
20	1	1/2	0.037	1.5	4.0	3.0	13.5			134.1		3.9			1.26	0.90	I
20	1	1/2	0.037	1.75	4.0	3.5	13.5			121.6		3.53			1.4	1.0	I
20	1	1/2	0.037	2.0	4.0	4.0	13.5			138.9		4.03			1.22	0.868	I

Mean = 1.38 1.00

Standard Deviation = 0.14 0.09

All Single Shear Connections

*1. One bolt
2. Two bolts perpendicular to line of stress
3. Three bolts perpendicular to line of stress

$^{**}(\sigma_b)_{cal} = 4.9\ C_2Fy$

$^{***}(\sigma_b)_{cal} = 3.5\ C_2Fy$

See Table 1 for the definition of type of failure

Table 3. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Double Shear)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
20A41DS	1/4	0.036	1.125	4.0	4.5	6.94	32.11	41.85	206.32	0.934	6.89	147.0	0.713	II	9
16C403DS	1/2	0.0591	2.0		4.0	8.46	31.95	43.95	224.03	1.0	7.01	156.6	0.7	II	9
16C503DS	1/2	0.0591	2.5		5.0	8.46	31.95	43.95	243.66	1.0	7.63	156.6	0.643	II	9
14E35DS	3/4	0.0783	2.625		3.5	9.58	54.44	70.4	242.20	0.919	4.84	245.2	1.011	I & II	10
10E36DS	1.0	0.143	3.5		3.5	6.98	59.5	71.85	199.35	0.797	4.2	232.4	1.16	II	10
10E46DS	1.0	0.143	4.5		4.5	6.98	59.5	71.85	201.5	0.797	4.2	232.4	1.16	II	10
20Z-L8	3/16	0.038	.66	2.08	3.52	4.93	75.7	81.7	206.0	0.643	4.23	238.5	1.16	II & I	6
1205XL7	3/4	0.106	2.63	3.75	3.5	7.08	81.6	81.6	252.0		4.81	257.1	1.02	II & I	
1205XL8	3/4		2.63	3.0	3.5	7.08			236.0		4.49		1.08	II & III	
1205XL9	7/8		3.06	3.5		8.25			242.0		4.62		1.06	II & III	
7Y-L32	5/8	0.183	2.19	2.98		3.42	82.6	82.6	247.0		4.65	258.3	1.05	II & I	
16FAXL15	1/2	0.062	1.75	2.5		8.06	30.1	45.9	161.8	1.0	5.38	147.5	0.912	II & III	
16FAXL17	1/2			5.0					136.0		4.52		1.08	II	
12FAX-L20	1/2	0.106		2.5		4.72	28.1	44.1	159.2		5.67	137.7	0.865	II & III	
12FAX-L21	1/2	0.106		5.0		4.72			178.4		6.35		0.772	II	
DS1-1	7/8	0.116	3.06	8.0	3.5	7.54	35.49	49.44	161.58	1.0	4.55	173.9	1.08	II	14
DS1-2		0.116	3.06						148.77		4.19		1.17		
DS2-1	1.0	0.115	3.5			8.7			139.13		3.92		1.25		
DS2-2		0.116	3.5			8.62			143.10		4.03		1.22		
DS3-1	7/8	0.181	3.06			4.83	38.1	62.08	209.94		5.51	186.7	0.889		
DS3-2		0.180	3.06			4.86			196.14		5.15		0.952		
DS4-1	1.0	0.182	3.5			5.49			229.12		6.01		0.815		
DS4-2		0.181				5.52			223.76		5.87		0.834		
DS5-1		0.259				3.86	45.07	67.54	221.62		4.92	220.8	0.996		
DS5-2		0.26				3.85	45.07		222.31		4.93		0.993		

$*(\sigma_b)_{cal} = 4.9\ C_2Fy$

Mean = 0.930

See Table 1 for definition of type of failure

Standard Deviation = 0.170

Table 4. Dimensions and Results of Bolted Connections without Washers-Bearing Strength Study [7] e/d > 2.5

Gage of Steel	Connection* Type	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^{**}_{cal}$ (ksi)	$(\sigma_b)^{***}_{cal}$ (ksi)	$\frac{(\sigma_b)^{**}_{cal}}{(\sigma_b)_{test}}$	$\frac{(\sigma_b)^{***}_{cal}}{(\sigma_b)_{test}}$	Failure Type
20	1	1/2	0.037	2.06	4.06	4.06	13.5	53.5	58.9	133.0	0.644	3.9	168.86	120.6	1.27	0.91	I & II
20	1	5/16	0.037	2.04	4.03	6.53	8.45			158.4		4.6			1.07	0.76	II
20	1	5/16	0.037	2.06	4.12	6.6	8.45			138.4		4.04			1.22	0.87	I & II
20	1	1/2	0.037	2.5	4.0	5.0	13.5			122.2		3.55			1.38	0.987	II
20	1	1/2	0.037	2.5	4.0	5.0	13.5			125.0		3.63			1.35	0.965	II
17	1	1/2	0.051	2.06	4.03	4.12	9.8	40.6	50.1	113.3	0.835	3.34	166.11	118.65	1.47	1.05	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.8			117.0		3.45			1.42	1.01	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.8			115.3		3.4			1.11	1.03	I & II
17	3	5/16	0.051	2.05	1.35	6.56	6.13			109.6		3.23			1.52	1.08	II
17	3	5/16	0.051	2.07	1.35	6.62	6.13			112.7		3.33			1.47	1.05	II
17	2	1/2	0.051	1.97	2.02	3.94	9.8			109.2		3.22			1.52	1.09	I & II
16	2	1/2	0.061	1.97	2.0	3.94	8.2	50.5	74.1	147.2	1.0	2.91	247.45	176.75	1.68	1.2	II
14	1	3/4	0.079	3.0	4.0	4.0	9.5	52.8	65.9	145.1	0.855	3.21	221.2	158.0	1.52	1.09	I & II
14	1	3/4	0.079	3.01	4.0	4.0	9.5			137.6		3.05			1.61	1.15	I & II
14	1	3/4	0.079	3.0	4.0	4.0	9.5			154.8		3.43			1.43	1.02	I & II
12	1	3/4	0.104	3.03	4.06	4.04	7.2	59.3	70.6	160.3	0.772	3.5	224.34	160.23	1.4	1.00	I & II
20	1	1/2	0.037	1.5	4.0	3.0	13.5	53.5	58.9	130.3	0.644	3.77	168.86	120.6	1.3	0.926	I
20	1	1/2	0.037	1.5	3.06	3.0	13.5			123.8		3.69			1.36	0.974	I
20	1	1/2	0.037	1.5	3.03	3.0	13.5			122.2		3.54			1.38	0.987	I
17	1	1/2	0.051	1.5	2.02	3.0	9.8	40.6	50.1	112.2	0.835	3.31	166.11	118.65	1.48	1.06	I
17	1	1/2	0.051	1.44	2.02	2.88	9.8			113.7		3.35	166.11	118.65	1.46	0.04	I
20	1	1/2	0.037	2.03	4.06	4.06	13.5	53.5	58.9	120.5	0.644	3.5	168.86	120.6	1.4	1.00	I
20	1	1/2	0.037	2.07	4.06	4.14	13.5			131.4		3.81			1.28	0.918	I
20	1	1/2	0.037	1.5	4.0	3.0	13.5			134.1		3.9			1.26	0.90	I
20	1	1/2	0.037	1.75	4.0	3.5	13.5			121.6		3.53			1.4	1.0	I
20	1	1/2	0.037	2.0	4.0	4.0	13.5			138.9		4.03			1.22	0.868	I

All Single Shear Connections

Mean = 1.38 1.00

Standard Deviation = 0.14 0.09

*1. One bolt
2. Two bolts perpendicular to line of stress
3. Three bolts perpendicular to line of stress

$**(\sigma_b)_{cal} = 4.9\ C_2Fy$

$***(\sigma_b)_{cal} = 3.5\ C_2Fy$

See Table 1 for the definition of type of failure

Table 5. Dimensions and Results of Single Shear Bolted Connections With Washers-Shear Strength Study

Spec No	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference No
20A11SS	1/4	0.0360	0.375	4.00	1.500	6.94	32.11	41.83	89.33	0.933	2.98	62.90	0.704	I	9
20A21SS	1/4		0.625		2.500				134.50	0.933	4.50	104.87	0.780	I	9
20A12SS	3/8		0.563		1.500	10.40			79.77		2.66	62.90	0.788	I	9
20A22SS	3/8		0.938		2.500	10.40			130.28		4.35	104.87	0.805	I	9
20A13SS	1/2		0.750		1.500	13.90			81.69		2.72	62.90	0.770	I	9
20A14SS	5/8		0.938		1.500	17.40			78.30		2.62	62.90	0.803	I	9
20A24SS	5/8		1.560		2.500	17.40			125.38		4.20	104.87	0.836	I & II	9
20A15SS	3/4		1.130		1.500	20.80			84.61		2.82	62.90	0.743	I	9
16C105SS	3/4	0.0591	0.750		1.000	12.70	31.95	43.81	58.89		2.00	41.73	0.709	I	9
16C205SS	3/4		1.500		2.000	12.70			109.87		3.70	83.47	0.760	I	9
14A11SS	1/4	0.0800	0.375		1.500	3.13	29.81	43.40	80.30	1.000	2.69	62.60	0.780	I	9
14A12SS	3/8		0.563		1.500	4.70			74.30		2.52	62.60	0.843	I	9
14A22SS	3/8		0.938		2.500				129.78		4.36	104.34	0.804	I	9
14A13SS	1/2		0.750		1.500	6.25			77.10		2.59	62.60	0.812	I	9
14A23SS	1/2		1.250		2.500				122.73		4.11	104.34	0.850	I	9
12A11SS	1/4	0.0931	0.375		1.500	2.70	25.60	41.15	77.99		3.05	53.76	0.689	I	9
12A12SS	3/8		0.563		1.500	4.03			80.49		3.15	53.76	0.668	I	9
12A14SS	5/8		0.938			6.71	26.65	41.40	76.53		2.87	56.60	0.731	I	9
18E12SS	3/8	0.0460	0.563			8.24	46.75	68.00	108.93		2.33	98.20	0.901	I	10
18E22SS	3/8	0.0460	0.938		2.500	8.24			197.62		4.23	163.63	0.828	I	10
18E14SS	5/8	0.0460	0.938		1.500	13.74			112.52		2.41	98.20	0.873	I	10
14E13SS	1/2	0.0780	0.750			6.40	54.44	70.40	111.30	0.920	2.23	105.20	0.945	I	10
14E23SS	1/2	0.0780	1.250		2.500	6.40			182.50		3.64	175.30	0.960	I	10
14E15SS	3/4		1.130		1.500	9.60			119.50		2.40	105.20	0.880	I	10

$^*(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Table 5 (con't)

Spec No	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference No
14E25SS	3/4	0.0780	1.880	4.00	2.500	9.60	54.44	70.40	170.90	0.920	3.41	175.30	1.030	I & II	10
10E15SS	3/4	0.1430	1.130		1.500	5.23	59.47	76.84	107.30		2.00	115.00	1.070	I	10
10E16SS	1.0		1.500		1.500	7.00			104.50		2.00	115.00	1.100	I	10
8E15SS	3/4	0.1901	1.130		1.500	3.95	56.45	76.98	107.10	1.000	1.90	118.50	1.110	I	10
12Y-L10	5/8	0.1060	2.110	4.12	3.370	5.90	72.40	72.80	204.00	0.643	4.40	219.65	1.080	I & II	6
7Y-L1	3/4	0.1830	0.620	1.50	0.833	4.10	83.10	83.80	62.00		1.17	62.30	1.000	I	6
7Y-L2	3/4		0.690	1.50	0.917	4.10			64.00		1.20	68.54	1.070	I	6
7Y-T3	3/4		0.620	1.50	0.833	4.10	86.40	91.30	58.50		1.06	64.80	1.110	I	6
7Y-L4	3/4		1.000	1.88	1.330	4.10	83.10	83.80	97.20		1.82	99.73	1.030	I	6
7Y-T4	3/4		1.000	1.88	1.330	4.10	86.40	91.30	102.00		1.84	103.70	1.020	I	6
7Y-T5	3/4	0.1830	1.750	3.00	2.330	4.10	86.40	91.30	186.00	0.643	3.34	181.45	0.976	I & II	6
SS1	7/8	0.1150	1.750	8.00	2.000	7.61	35.49	49.44	128.45	1.000	3.62	99.40	0.774	I	14
SS4	1.0	0.1160	2.000		2.000	8.62			122.51		3.45	99.40	0.811	I	14
SS7	7/8	0.1810	1.750		2.000	4.83	38.10	62.08	142.07		3.73	106.70	0.751	I	14
SS10	1.0	0.1840	2.000		2.000	5.43			137.50		3.61	106.70	0.776	I	14
SS13	1.0	0.2610	2.000		2.000	3.83	45.07	67.54	142.34		3.16	126.20	0.791	I	14
-	1/2	0.0370	1.030	4.00	2.060	13.50	53.50	58.90	159.50	0.644	4.63	99.37	0.623	I	7
-	1/2	0.0370	1.060	4.03	2.200	13.50			162.70		4.72	106.12	0.652	I	7
-	1/2	0.0370	1.000	4.00	2.000	13.50			149.73		4.35	96.47	0.644	I	7
-	1/2	0.0510	0.970	4.06	1.940	9.80	40.60	50.10	134.10	0.835	3.95	92.10	0.687	I	7
-	1/2	0.0510	1.020	4.06	2.040	9.80			136.90		4.04	96.82	0.707	I	7
-	1/2	0.0610	1.030	4.03	2.060	8.20	50.50	74.10	173.10	1.000	3.43	145.60	0.841	I & II	7
-	1/2	0.0610	1.030	4.06	2.060	8.20			167.90		3.32	145.60	0.867	I & II	7

$^*(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Mean = 0.850

Standard Deviation = 0.140

Table 5. Dimensions and Results of Single Shear Bolted Connections With Washers-Shear Strength Study

Spec No	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference No
20A11SS	1/4	0.0360	0.375	4.00	1.500	6.94	32.11	41.83	89.33	0.933	2.98	62.90	0.704	I	9
20A21SS	1/4		0.625		2.500				134.50	0.933	4.50	104.87	0.780	I	9
20A12SS	3/8		0.563		1.500	10.40			79.77		2.66	62.90	0.788	I	9
20A22SS	3/8		0.938		2.500	10.40			130.28		4.35	104.87	0.805	I	9
20A13SS	1/2		0.750		1.500	13.90			81.69		2.72	62.90	0.770	I	9
20A14SS	5/8		0.938		1.500	17.40			78.30		2.62	62.90	0.803	I	9
20A24SS	5/8		1.560		2.500	17.40			125.38		4.20	104.87	0.836	I & II	9
20A15SS	3/4		1.130		1.500	20.80			84.61		2.82	62.90	0.743	I	9
16C105SS	3/4	0.0591	0.750		1.000	12.70	31.95	43.81	58.89		2.00	41.73	0.709	I	9
16C205SS	3/4		1.500		2.000	12.70			109.87		3.70	83.47	0.760	I	9
14A11SS	1/4	0.0800	0.375		1.500	3.13	29.81	43.40	80.30	1.000	2.69	62.60	0.780	I	9
14A12SS	3/8		0.563		1.500	4.70			74.30		2.52	62.60	0.843	I	9
14A22SS	3/8		0.938		2.500				129.78		4.36	104.34	0.804	I	9
14A13SS	1/2		0.750		1.500	6.25			77.10		2.59	62.60	0.812	I	9
14A23SS	1/2		1.250		2.500				122.73		4.11	104.34	0.850	I	9
12A11SS	1/4	0.0931	0.375		1.500	2.70	25.60	41.15	77.99		3.05	53.76	0.689	I	9
12A12SS	3/8		0.563		1.500	4.03			80.49		3.15	53.76	0.668	I	9
12A14SS	5/8		0.938			6.71	26.65	41.40	76.53		2.87	56.60	0.731	I	9
18E12SS	3/8	0.0460	0.563			8.24	46.75	68.00	108.93		2.33	98.20	0.901	I	10
18E22SS	3/8	0.0460	0.938		2.500	8.24			197.62		4.23	163.63	0.828	I	10
18E14SS	5/8	0.0460	0.938		1.500	13.74			112.52		2.41	98.20	0.873	I	10
14E13SS	1/2	0.0780	0.750			6.40	54.44	70.40	111.30	0.920	2.23	105.20	0.945	I	10
14E23SS	1/2	0.0780	1.250		2.500	6.40			182.50		3.64	175.30	0.960	I	10
14E15SS	3/4		1.130		1.500	9.60			119.50		2.40	105.20	0.880	I	10

$^*(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Table 5 (con't)

Spec No	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference No
14E25SS	3/4	0.0780	1.880	4.00	2.500	9.60	54.44	70.40	170.90	0.920	3.41	175.30	1.030	I & II	10
10E15SS	3/4	0.1430	1.130		1.500	5.23	59.47	76.84	107.30		2.00	115.00	1.070	I	10
10E16SS	1.0		1.500		1.500	7.00			104.50		2.00	115.00	1.100	I	10
8E15SS	3/4	0.1901	1.130		1.500	3.95	56.45	76.98	107.10	1.000	1.90	118.50	1.110	I	10
12Y-L10	5/8	0.1060	2.110	4.12	3.370	5.90	72.40	72.80	204.00	0.643	4.40	219.65	1.080	I & II	6
7Y-L1	3/4	0.1830	0.620	1.50	0.833	4.10	83.10	83.80	62.00		1.17	62.30	1.000	I	6
7Y-L2	3/4		0.690	1.50	0.917	4.10			64.00		1.20	68.54	1.070	I	6
7Y-T3	3/4		0.620	1.50	0.833	4.10	86.40	91.30	58.50		1.06	64.80	1.110	I	6
7Y-L4	3/4		1.000	1.88	1.330	4.10	83.10	83.80	97.20		1.82	99.73	1.030	I	6
7Y-T4	3/4		1.000	1.88	1.330	4.10	86.40	91.30	102.00		1.84	103.70	1.020	I	6
7Y-T5	3/4	0.1830	1.750	3.00	2.330	4.10	86.40	91.30	186.00	0.643	3.34	181.45	0.976	I & II	6
SS1	7/8	0.1150	1.750	8.00	2.000	7.61	35.49	49.44	128.45	1.000	3.62	99.40	0.774	I	14
SS4	1.0	0.1160	2.000		2.000	8.62			122.51		3.45	99.40	0.811	I	14
SS7	7/8	0.1810	1.750		2.000	4.83	38.10	62.08	142.07		3.73	106.70	0.751	I	14
SS10	1.0	0.1840	2.000		2.000	5.43			137.50		3.61	106.70	0.776	I	14
SS13	1.0	0.2610	2.000		2.000	3.83	45.07	67.54	142.34		3.16	126.20	0.791	I	14
-	1/2	0.0370	1.030	4.00	2.060	13.50	53.50	58.90	159.50	0.644	4.63	99.37	0.623	I	7
-	1/2	0.0370	1.060	4.03	2.200	13.50			162.70		4.72	106.12	0.652	I	7
-	1/2	0.0370	1.000	4.00	2.000	13.50			149.73		4.35	96.47	0.644	I	7
-	1/2	0.0510	0.970	4.06	1.940	9.80	40.60	50.10	134.10	0.835	3.95	92.10	0.687	I	7
-	1/2	0.0510	1.020	4.06	2.040	9.80			136.90		4.04	96.82	0.707	I	7
-	1/2	0.0610	1.030	4.03	2.060	8.20	50.50	74.10	173.10	1.000	3.43	145.60	0.841	I & II	7
-	1/2	0.0610	1.030	4.06	2.060	8.20			167.90		3.32	145.60	0.867	I & II	7

$*(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

Mean = 0.850

See Table 1 for the definition of type of failure.

Standard Deviation = 0.140

Table 6. Dimensions and Results of Bolted Connections Without Washers Shear Strength Study [7] $e/d \leq 2.5$

Gage of Steel	Connection* Type	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)_{cal}$** (ksi)	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type
20	1	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	129.20	0.644	3.74	96.50	0.747	I & II
20	1	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	127.70	0.644	3.70	96.50	0.756	I & II
20	1	1/2	0.037	0.50	4.00	1.00	13.5	53.5	58.9	90.81	0.644	2.64	48.23	0.531	I
20	1	1/2	0.037	0.50	4.00	1.00	13.5	53.5	58.9	82.20	0.644	2.39	48.23	0.587	I
20	3	1/2	0.037	1.00	3.94	2.00	13.5	53.5	58.9	116.60	0.644	3.38	96.50	0.828	I
20	3	1/2	0.037	1.00	3.94	2.00	13.5	53.5	58.9	116.76	0.644	3.39	96.50	0.826	I
20	2	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	118.40	0.644	3.43	96.50	0.815	I
20	2	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	116.80	0.644	3.39	96.50	0.826	I
16	1	1/2	0.061	0.51	4.00	1.02	8.2	50.5	74.1	90.82	1.000	1.80	72.11	0.794	I & II
16	1	1/2	0.061	0.52	4.00	1.04	8.2	50.1	74.1	101.30	1.000	2.00	73.53	0.726	I & II
16	3	1/2	0.061	1.00	4.03	2.00	8.2	50.1	74.1	143.20	1.000	2.86	140.30	0.980	I & II
16	3	1/2	0.061	1.00	4.06	2.00	8.2	50.1	74.1	147.50	1.000	2.94	140.30	0.951	I & II

All Single Shear Connections

Mean = 0.780

Standard deviation = 0.130

* 1 One Bolt
 2 Two bolts parallel to the line of stress
 3 Three bolts parallel to the line of stress

$**(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Table 7. Dimensions and Results of Double Shear Bolted Connections with Washers-Shear Strength Study

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$	$(\sigma_b)_{cal}/(\sigma_b)_{test}$	Failure Type	Reference
20A11DS	1/4	0.036	0.375	4.0	1.5	6.94	32.11	41.85	95.85	0.934	3.2	62.98	0.659	I	9
20A21DS	1/4		0.625		2.5				142.75		4.76	104.98	0.735	I	
20A12DS	3/8		0.563		1.5	10.42			93.89		3.13	62.98	0.671	I	
20A13DS	1/2		0.75			13.9			84.42		2.82	62.98	0.746	I	
20A14DS	5/8		0.938			17.36			88.09		2.93	62.98	0.715	I	
20A15DS	3/4		1.125			20.83			88.7		2.96	62.98	0.71	I	
16C103DS	1/2	0.059	0.5		1.0	8.46	31.95	43.81	58.55	1.0	1.83	44.73	0.764	I	
16C203DS	1/2		1.0		2.0	8.46			112.69		3.53	89.5	0.794	I	
14A11DS	1/4	0.08	0.375		1.5	3.13	29.81	43.4	78.37		2.63	62.6	0.799	I	
14A21DS	1/4		0.625		2.5	3.13			131.86		4.42	104.34	0.791	I	
14A12DS	3/8		0.563		1.5	4.69			83.47		2.8	62.6	0.75	I	
14A12DS	3/8		0.938		2.5	4.69			129.33		4.34	104.34	0.807	I	
14A13DS	1/2		0.75		1.5	6.25			81.91		2.75	62.6	0.764	I	
14A23DS	1/2		1.25		2.5	6.25			130.58		4.38	104.34	0.799	I	
12A11DS	1/4	0.0931	0.375		1.5	2.68	26.0	41.15	82.18		3.17	54.6	0.664	I	
12A21DS	1/4		0.625		2.5	2.68			134.81		5.19	91.0	0.675	I	
12A12DS	3/8		0.563		1.5	4.03			79.04		3.04	54.6	0.691	I	
12A22DS	3/8		0.938		2.5	4.03			134.39		5.17	91.0	0.677	I	
12A14DS	5/8		0.938		1.5	6.71			83.82		3.22	54.6	0.651	I	
12A24DS	5/8		1.563		2.5	6.71			127.73		4.92	91.0	0.712	I	
10A12DS	3/8	0.143	0.563		1.5	2.62	36.6	48.0	84.84	0.945	2.46	72.63	0.856	I	
10A22DS	3/8	0.143	0.938		2.5	2.62			133.56		3.86	121.05	0.906	I	
8B23DS	1/2	0.188	1.25		2.5	2.66	35.15	47.1	124.75	0.973	3.65	119.71	0.96	I	
8B25DS	3/4	0.188	1.88		2.5	4.0			129.16		3.78	119.71	0.927	I	
18E12DS	3/8	0.046	0.563		1.5	8.24	46.75	68.0	110.71	1.0	2.37	98.2	0.887	I	10
18E22DS	3/8		0.938		2.5	8.24			185.37		3.97	163.63	0.883	I	
18E14DS	5/8		0.938		1.5	13.74			110.91		2.37	98.2	0.885	I	
18E24DS	5/8		1.563		2.5	13.74			171.97		3.68	163.63	0.951	I	
14E13DS	1/2	0.078	0.75		1.5	6.39	54.44	70.4	122.4	0.919	2.45	105.06	0.858	I	
14E13DS	1/2		1.25		2.5	6.39			190.9		3.82	175.1	0.917	I	
14E15DS	3/4		1.125		1.5	9.58			121.35		2.43	105.06	0.866	I	
10E12DS	3/8	0.143	0.563		1.5	2.61	59.5	71.85	101.55	0.797	2.15	99.63	0.981	I	
10E13DS	1/2		0.75		1.5	3.5			107.1		2.26	99.63	0.93	I	
10E23DS	1/2		1.25		2.5	3.5			180.8		3.81	165.98	0.918	I	
10E15DS	3/4		1.13		1.5	5.23			121.45		2.57	99.63	0.82	I	

Table 7.(con't)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
10E26DS	1.0	0.143	2.5	4.0	2.5	7.0	59.5	71.85	167.0	0.797	2.53	165.98	0.994	I	10
8E15DS	3/4	0.19	1.125		1.5	3.95	56.45	76.98	108.95	1.0	1.93	118.55	1.09	I	
8E25DS	3/4		1.875		2.5	3.95			158.3		2.81	197.6	1.25	I & II	
7Y-L22	1/2	0.183	0.88	5.0	1.75	2.73	83.1	83.8	136.8	0.643	2.57	130.91	0.957	I	6
7Y-L23	1/2		0.75		1.5				112.3		2.1	112.2	1.0	I	6
7Y-L24	1/2		1.4		2.8				263.0		4.91	209.46	0.796	I & II	6
7Y-L25	1/2		1.5	3.33	3.0				240.0		4.5	224.4	0.935	I & II	6
20Z-L5	1/2	0.038	1.0	2.5	2.0	13.16	75.7	81.7	130.8	0.727	2.38	154.12	1.18	I & II	6
20Z-L7	3/16		0.47	2.08	2.5	4.93			192.0		3.5	192.62	1.0	I	6
1605X-L5	1/2	0.062	1.0	2.5	2.0	8.06	8›.25	83.25	157.0	0.643	2.94	149.9	0.955	I	6
1605X-L6	1/2		1.4	5.0	2.8	8.06	87.6	87.6	224.0		4.0	220.81	0.986	I & II	6
1205X-L10	1/2	0.106	1.4	5.0	2.8	4.72	80.5	80.5	206.0		4.0	202.93	0.985	I & II	6
7Y-L31	1/2	0.183	1.5	2.5	3.0	2.73	82.6	82.6	222.5		4.18	223.07	1.0	I	6
16FAX-L14	1/2	0.062	1.25	2.5	2.5	8.06	30.1	45.9	101.6	1.0	3.38	105.4	1.04	I & II	6
12FAX-L19	1/2	0.106	1.25	2.5	2.5	4.72	28.1	44.1	120.2		4.28	98.4	0.818	I & II	6

*$(\sigma_b) = 1.4(e/d)\ C_2Fy$

Mean = 0.860

See Table 1 for the definition of type of failure.

Standard Deiviation = 0.140

Table 8. Dimensions and Results of Bolted Connections with Washers-Tensile Strength Study (Single Shear)

Spec. No.	d (in)	t (in)	s (in)	e/d	d/s	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{Fu}$	$(\sigma_{net})^{*}_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type	Reference
20A41SS1	1/4	0.0346	4.0	4.5	0.0625	7.23	32.11	41.85	15.5	0.370	12.03	0.776	III	9
20A41SS2	1/4	0.0349		"	"	7.16			14.87	0.355	12.03	0.809	III	9
20A22SS1	3/8	0.0354		2.5	0.094	10.6			13.5	0.323	16.0	1.185	I & III	9
20A32SS1	3/8	0.0335		3.5	0.094	11.2			14.74	0.352	16.0	1.085	I & III	9
20A32SS2	3/8	0.0342		3.5	0.094	10.96			19.94	0.476	16.0	0.802	III	9
20A42SS1	3/8	0.0349		4.5	0.094	10.74			14.35	0.343	16.0	1.115	I & III	9
20A42SS3	3/8	0.036		4.5	0.094	10.42			13.1	0.313	16.0	1.221	III	9
20A23SS1	1/2	0.0352		2.5	0.125	14.2			17.15	0.41	19.9	1.16	I & III	9
20A43SS1	1/2	0.0352		4.5	0.125	14.2			17.19	0.411	19.9	1.157	I & III	9
20A43SS3	1/2	0.0361		4.5	0.125	13.9			20.55	0.491	19.9	0.968	III	9
20A34SS	5/8	0.0359		3.5	0.156	17.4			24.64	0.59	23.77	0.965	III	9
20A44SS	5/8	0.0353		4.5	0.156	17.7			21.9	0.523	23.77	1.09	III	9
20A25SS1	3/4	0.0357		2.5	0.188	21.0			25.3	0.605	27.8	1.1	III	9
20A35SS1	3/4	0.0357		3.5	0.188	21.0			25.13	0.60	27.8	1.1	III	9
16C305SS	3/4	0.0591		3.0	0.188	12.7	32.0	44.0	31.28	0.711	29.22	0.934	III	9
16C505SS	3/4	0.0591		5.0	0.188	12.7			30.32	0.690	29.22	0.964	III	9
14A23SS1	1/2	0.0832		2.5	0.125	6.0	29.8	43.4	17.97	0.414	20.62	1.15	I & III	9
14B25SS1	3/4	0.0798		2.5	0.188	9.4			25.12	0.579	28.82	1.15	III	9
14B35SS1	3/4	0.0771		3.5	0.188	9.73			23.79	0.548	28.82	1.21	III	9
14B45SS	3/4	0.0814		4.5	0.188	9.21			26.21	0.604	28.82	1.1	III	9
14B26SS1	1.0	0.0768		2.5	0.25	13.0			33.33	0.768	36.89	1.11	III	9
14B36SS1	3/4	0.0741		3.5	0.188	10.12			33.31	0.767	28.82	0.865	III	9
14B46SS1	3/4	0.0789		4.5	0.188	9.51			35.9	0.827	28.82	0.803	III	9
12A34SS1	5/8	0.0922		3.5	0.156	6.78	26.0	41.15	37.2	0.904	23.4	0.629	III	9
12A44SS1	5/8	0.0922		4.5	0.156	6.78			24.3	0.591	23.4	0.963	III	9
8B45SS1	3/4	0.1867		4.5	0.188	4.02	32.0	46.0	29.07	0.632	30.54	1.05	I & III	9
8B26SS1	1.0	0.1893		2.5	0.25	5.28			43.7	0.95	39.1	0.895	III	9
8B46SS1	1.0	0.1884		4.5	0.25	5.31			46.98	1.02	39.1	0.832	III	9
18E42SS1	3/8	0.0451		4.5	0.094	8.31	46.75	68.0	20.85	0.307	26.0	1.25	III & I	10
18E24SS1	5/8	0.0441		2.5	0.156	14.2			29.78	0.438	38.62	1.3	I & III	10
18E34SS	5/8	0.0444		3.5	0.156	14.08			37.8	0.556	38.62	1.02	III	10
18E44SS1	5/8	0.0448		4.5	0.156	13.95			35.04	0.515	38.62	1.1	III	10
14E35SS1	3/4	0.0789		3.5	0.188	9.51	54.44	70.4	47.95	0.681	46.75	0.975	III	10
14E45SS1	3/4	0.0781		4.5	0.188	9.6			55.45	0.788	46.75	0.843	III	10
10E26SS1	1.0	0.1455		2.5	0.25	6.87	59.5	71.85	55.25	0.77	61.1	1.11	III	10
14G25SS	3/4	0.0766	2.0	2.5	0.375	9.8	29.8	43.4	49.4	1.14	43.4	0.879	III	10
14G35SS	3/4	0.0753		3.5	0.375	9.96			47.0	1.08	43.4	0.923	III	10
14G45SS	3/4	0.0795		4.5	0.375	9.43			46.5	1.07	43.4	0.933	III	10

Mean = 1.010

Standard Deviation = 0.150

$^{*}(\sigma_{net})_{cal} = (.1 + 3\ d/s)\ Fu$

See Table 1 for the definition of type of failure.

Table 9. Dimensions and Results of Single Shear Connections With Washers-Tensile Strength Study[6]

Spec No	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})_{cal}^{*}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type
12Y-L12	1/2	0.104	2.660	3.500	0.188	4.81	72.40	72.80	50.96	0.700	48.34	0.949	II & III
12Y-L13	5/8		3.330	3.480		6.01			36.00	0.495	48.34	1.340	I & II & III
12Y-L14	3/4		3.930	3.460	0.191	7.21			70.64	0.970	49.00	0.694	II & III
12Y-L15	3/8		1.520	3.990	0.247	3.61			66.12	0.910	61.22	0.926	I & II & III
12Y-L17	5/8		2.548	3.400	0.245	6.01			54.70	0.751	60.80	1.110	I & II & III
12Y-L18	3/4		3.040	3.530	0.247	7.21			52.22	0.717	61.22	1.170	II & III
12Y-L19	7/8		3.530	3.430	0.248	8.41			52.55	0.722	61.44	1.170	III
7Y-T3	3/4	0.183	1.500	0.833	0.500	4.10	86.40	91.30	84.74	0.928	91.30	1.080	III
7Y-L5			3.750	2.500	0.200		83.10	83.90	52.00	0.620	58.73	1.130	I & II & III
7Y-L6			3.750	5.000			83.10	83.10	79.00	0.951	58.73	0.743	II & III
12Y-L27	3/8	0.105	0.872	5.330	0.430	3.57	87.00	88.10	85.00	0.965	88.10	1.040	III
12Y-L28	5/8	0.105	1.500	4.000	0.420	5.95	87.00	88.10	88.70	1.010	88.10	0.993	III
7Y-T30	3/4	0.183	1.870	3.330	0.400	4.10	87.00	91.00	96.60	1.060	91.00	0.942	III
7Y-L20			1.500	1.500	0.500		83.10	83.80	84.60	1.010	83.80	0.991	III
7Y-L21			2.500	3.200	0.300				83.10	0.992	83.80	1.010	III
20Z-L1	1/2	0.039	1.500	3.500	0.330	12.82	75.50	81.70	85.30	1.040	81.70	0.960	III
20Z-L2				2.000					74.90	0.917	81.70	1.090	I & II & III
20Z-L3	3/4		2.500	2.000	0.300	19.23			63.80	0.781	81.70	1.280	I & II & III
20Z-T10	1/2		1.500	3.500	0.330	12.82	94.40	99.80	70.80	0.710	99.80	1.400	III
20Z-T11			2.500	3.000	0.200				40.23	0.403	70.00	1.740	II & III
1605X-L1	3/4	0.065	2.500	3.000	0.300	11.54	83.25	83.25	81.30	0.977	83.25	1.020	III
16FAX-L16	1/2	0.060		3.500	0.200	8.33	30.10	45.90	41.30	0.900	32.13	0.778	II & III

$*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u$

Mean = 1.070

See Table 1 for the definition of type of failure.

Standard Deviation = 0.230

Table 10. Dimensions and Results of Bolted Connections with Washers-Tensile Strength Study (Double Shear)

Spec. No.	d (in)	t (in)	s (in)	e/d	d/s	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{Fu}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type	Reference
20A21DS2	1/4	0.0347	4.0	2.5	0.063	7.2	32.11	41.85	9.66	0.231	12.1	1.25	I & III	9
20A22DS	3/8	0.0344	.		0.094	10.9			14.84	0.355	16.0	1.08	I & III	9
20A23DS1	1/2	0.0354			0.125	14.12			20.8	0.497	19.9	0.957	I & III	9
20A33DS1	1/2	0.0360		3.5		13.9			23.6	0.564		0.843	III	9
20A43DS	1/2	0.0356		4.5		14.04			29.0	0.693		0.686	III	9
20A34DS	5/8	0.0354		3.5	0.156	17.66			35.81	0.856	23.77	0.664	III	9
20A44DS1	5/8	0.036		4.5		17.36			34.56	0.826		0.688	III	9
20A25DS	3/4	0.0355		2.5	0.188	21.13			29.86	0.714	27.8	0.931	III	9
20A35DS1	3/4	0.0357		3.5		21.01			35.68	0.853	27.8	0.779	III	9
16C403DS1	1/2	0.0591		4.0	0.125	8.46	32.0	44.0	31.33	0.712	20.9	0.667	III	9
16C503DS1	1/2			5.0					34.98	0.795		0.597	III	9
14A43DS1	1/2	0.077		4.5		6.49	29.8	43.4	29.77	0.686	20.62	0.693	III	9
14B25DS1	3/4	0.0797		2.5	0.188	9.41			28.38	0.654	28.82	1.02	III	9
14B35DS1	3/4	0.077		3.5		9.74			34.27	0.79		0.841	III	9
14B26DS1	1.0	0.076		2.5	0.25	13.23			37.6	0.866	36.9	0.981	III	9
14B36DS1	1.0	0.0734		3.5	0.25	13.62			42.39	0.977		0.870	III	9
12A34DS1	5/8	0.0922		3.5	0.156	6.78	26.0	41.15	31.83	0.774	23.37	0.734	III	9
12A44DS1	5/8			4.5					36.87	0.896		0.634	III	9
8B35DS1	3/4	0.197		3.5	0.188	3.81	32.0	46.0	41.4	0.90	30.54	0.743	III	9
8B45DS1	3/4	0.1808		4.5		4.15			46.5	1.01		0.657	III	9
8B45DS1	1.0	0.191		2.5	0.25	5.24			43.35	0.942	39.1	0.902	III	9
18E34DS1	5/8	0.0451		3.5	0.156	13.86	46.75	68.0	43.98	0.647	38.62	0.878	I & III	9
18E44DS1	5/8	0.0453		4.5	0.156	13.8			45.84	0.674		0.842	I & III	10
14E25DS1	3/4	0.0781		2.5	0.188	9.6	54.44	70.4	42.1	0.598	46.75	1.11	III	10
14E45DS1	3/4	0.0781		4.5		9.54			67.4	0.957		0.694	III	10
10E25DS1	3/4	0.1351		2.5		5.55	59.5	71.85	44.85	0.624	47.71	1.06	I & III	10
10E16DS1	1.0	0.1421		1.5	0.25	7.04			35.4	0.493	61.1	1.73	I & III	10
10E46DS1	1.0	0.1411		4.5		7.09			69.4	0.966		0.88	III	10
14G25DS1	3/4	0.0768	2.0	2.5	0.375	9.77	29.8	43.4	47.8	1.1	43.4	0.908	III	10
14G35DS	3/4	0.0760		3.5	0.375	9.87			48.3	1.11	43.4	0.90	III	10
14G45DS	3/4	0.0755		4.5	0.375	9.93			49.7	1.15	43.4	0.87	III	10

$*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u$

Mean = 0.870

Standard Deviation = 0.220

See Table 1 for the definition of type of failure

Table 11. Dimensions and Results of Double Shear Bolted Connections With Washers-Tensile Strength Study [6]

Spec No	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type
20Z-L9	3/4	0.039	2.5	3.0	0.30	19.23	75.50	81.70	74.00	0.906	81.70	1.100	II & III
20ZT13							99.40	99.80	74.45	0.746	99.80	1.340	II & III
1605X-L2		0.065				11.54	83.25	83.25	85.70	1.030	83.25	0.971	III
1605XL3				2.0					68.72	0.825		1.210	I & II & III
1205X-L8		0.105	3.0	3.5	0.25	7.14	81.60	81.60	81.85	1.000	69.36	0.847	II & III
1205X-L9	7/8		3.5	3.5		8.33			83.25	1.020	69.36	0.833	II & III
1205X-L11	3/4		2.5	3.0	0.30	7.14	80.50	80.50	77.30	0.960	80.50	1.040	III
7Y-L32	5/8	0.183	3.0	3.5	0.21	3.42	82.60	82.60	66.20	0.801	60.30	0.911	I & II & III
16FAX-L12	3/4	0.060	2.5	3.0	0.30	12.50	30.10	45.90	46.00	1.000	45.90	0.998	III
16FAX-L13			2.5	3.5					46.20	1.010		0.994	III
16FAXL15	1/2		2.5		0.20	8.33			43.87	0.956	32.13	0.732	II & III
1610XL18	3/4			3.0	0.30	12.50	78.40	81.50	84.32	1.030	81.50	0.967	III
12FAXL18	3/4	0.107		3.0	0.30	7.01	28.10	44.10	45.10	1.020	44.10	0.987	III
12FAXL20	1/2			3.5	0.20	4.67			41.10	0.932	30.87	0.751	II & III
1615XL22	3/4	0.600		3.0	0.30	12.50	45.40	54.70	61.80	1.180	54.70	0.885	III
1615XL23	1/2				0.20	8.33			50.90	0.931	38.30	0.752	II & III
1625XL26	3/4				0.30	12.50	38.50	49.10	57.17	1.160	49.10	0.859	III
1625XL27	1/2				0.20	8.33			42.50	0.866	34.37	0.808	II & III
1625XL28	1/2			3.5	0.20				44.50	0.906		0.772	II & III
1210XL32	3/4	0.107		3.0	0.30	7.01	70.10	72.80	77.70	1.070	72.80	0.937	III
1210XL25	1/2		2.0	3.5	0.25	4.67			77.10	1.060	61.88	0.803	II & III
1215XL26	3/4		2.5	3.0	0.30	7.01	65.20	69.30	66.00	0.952	69.30	1.050	III
1215XL29	1/2		2.0	3.5	0.25	4.67			69.83	1.010	58.91	0.844	II & III
1225X-L30	3/4		2.5	3.0	0.30	7.01	36.60	50.00	53.61	1.070	50.00	0.933	III
1225XL31	1/2				0.20	4.67			42.40	0.848	35.00	0.825	II & III
1225XL32				3.5					42.50	0.850		0.823	II & III
1225XL33			2.0		0.25				51.50	1.030	42.50	0.825	II & III

$*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u$

Mean = 0.920

See Table 1 for the definition of type of failure.

Standard Deviation = 0.140

Table 12. Dimensions and Results of Multi-Bolted Connections With Washers-Tensile Strength Study [5]

Spec No	No of Bolts	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})_{cal}^*$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type
4F16A	1	3/4	0.060	4.01	4.00	0.1875	12.50	31.00	44.40	23.40	0.527	29.42	1.260	II & III
8F351	1	1 1/8	0.185	4.00	2.67	0.2810	6.08	55.70	77.40	68.70	0.887	73.00	1.060	II & III
14F451	1	1/2	0.078		6.00	0.1250	6.41	62.50	76.20	28.40	0.373	36.20	1.270	II & III
16A15	1	1/2	0.060				8.33	31.60	45.00	20.00	0.445	21.40	1.070	III
3C16A	2				3.50			31.00	44.40	37.60	0.847	32.75	0.871	II & III
4C16A	2	3/4	0.058	4.01	2.33	0.1875	12.93			40.00	0.903	36.91	0.923	II & III
8F352	2	1 1/8	0.185	4.00	2.67	0.2810	6.08	55.70	77.40	80.40	1.040	75.20	0.935	II & III
10F452	2	3/4	0.144		3.33	0.1875	5.21	62.80	80.70	74.60	0.926	67.10	0.900	III
14F452	2	1/2	0.078		5.00	0.1250	6.41	62.50	76.20	64.00	0.841	56.20	0.878	II & III
316A1	3		0.060		3.50		8.33	31.60	45.00	37.80	0.840	37.13	0.982	III
316A2	3									42.00	0.933		0.884	III
116A3	3	3/4			2.33	0.1875	12.50			43.50	0.968	39.94	0.918	III
216A3	3									43.00	0.956		0.929	III
16051A	3	1/2			4.00	0.1250	8.33	84.90	84.90	85.00	1.000	70.04	0.824	III
16052A	3	3/4			2.33	0.1875	12.50			100.00	1.180	75.35	0.754	III
16101A	3	1/2			4.00	0.1250	8.33	75.60	79.30	81.00	1.020	65.42	0.808	III
16102A	3	3/4			2.33	0.1875	12.50			86.40	1.090	70.40	0.815	III
7085S	3	5/8	0.184	3.22	5.00	0.1940	3.40	85.00	85.00	86.40	1.020	76.00	0.880	III
7091S	3	5/8	0.182	3.30		0.1940		86.25	86.25	84.80	0.983	76.76	0.905	III
7092S	3		0.183	4.23	6.80	0.1480				84.75	0.983	73.14	0.863	III
7093S	3		0.185							83.60	0.970		0.875	III

$*(\sigma_{net})_{cal} = (1 - .9r + 3rd/s)F_u$

See Table 1 for the definition of type of failure.

Mean = 0.930

Stanard Deviation = 0.130

Table 13. Torques Used in Installation of A307 Bolts (Cornell Tests)[3]

Bolt Diam. in.	Torque ft. lb.
1/4	5
3/8	14
1/2	40
5/8	50
3/4	110
1	250

Table 14. Torques Used in Installation of High Strength Bolts (Cornell Tests)[4]

Bolt Diam. in.	Torque ft. lb
1/4	11.0
3/8	37.5
1/2	95.0
5/8	190.0
3/4	335.0
1.0	750.0

Table 15. Bolt Tension Specified by the Research Council on Riveted and Bolted Structural Joints [21]

Bolt Diam. in.	Minimum Bolt Tension, kips	
	A325 Bolts	A490 Bolts
1/2	12	15
5/8	19	24
3/4	28	35
7/8	39	49
1	51	64
1 1/8	56	80
1 1/4	71	102
1 3/8	85	121
1 1/2	103	148

APPENDIC C

Figures

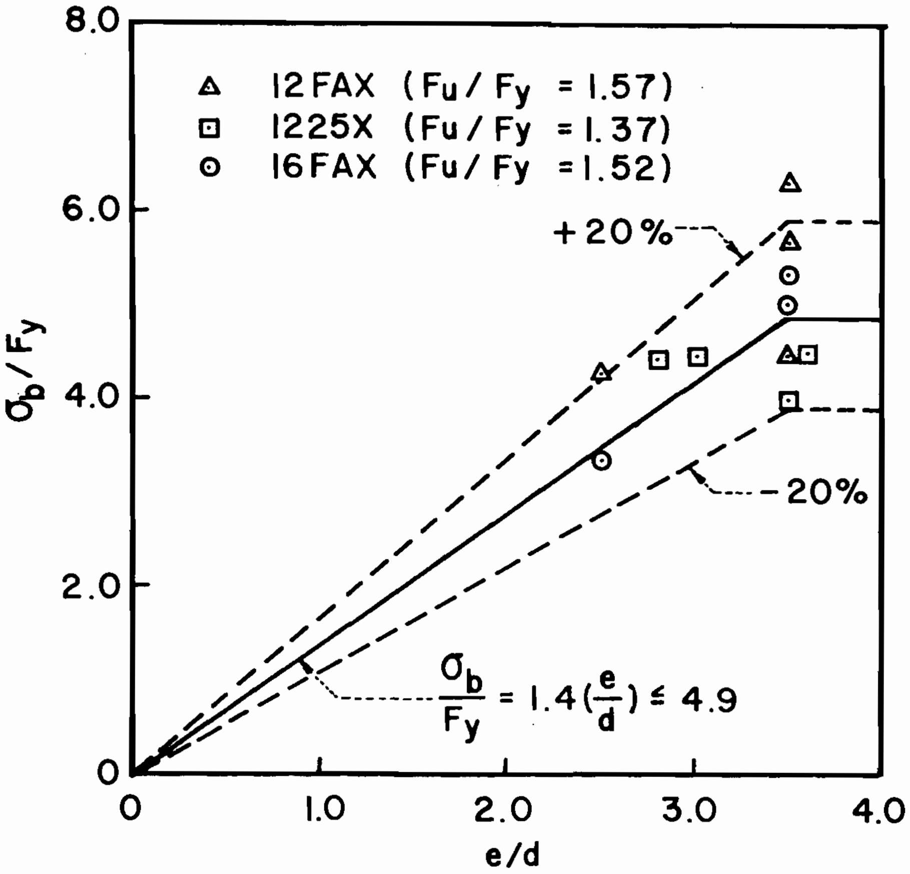

Fig. 1 Effect of Ductility ($F_u/F_y \geq 1.35$)[6]

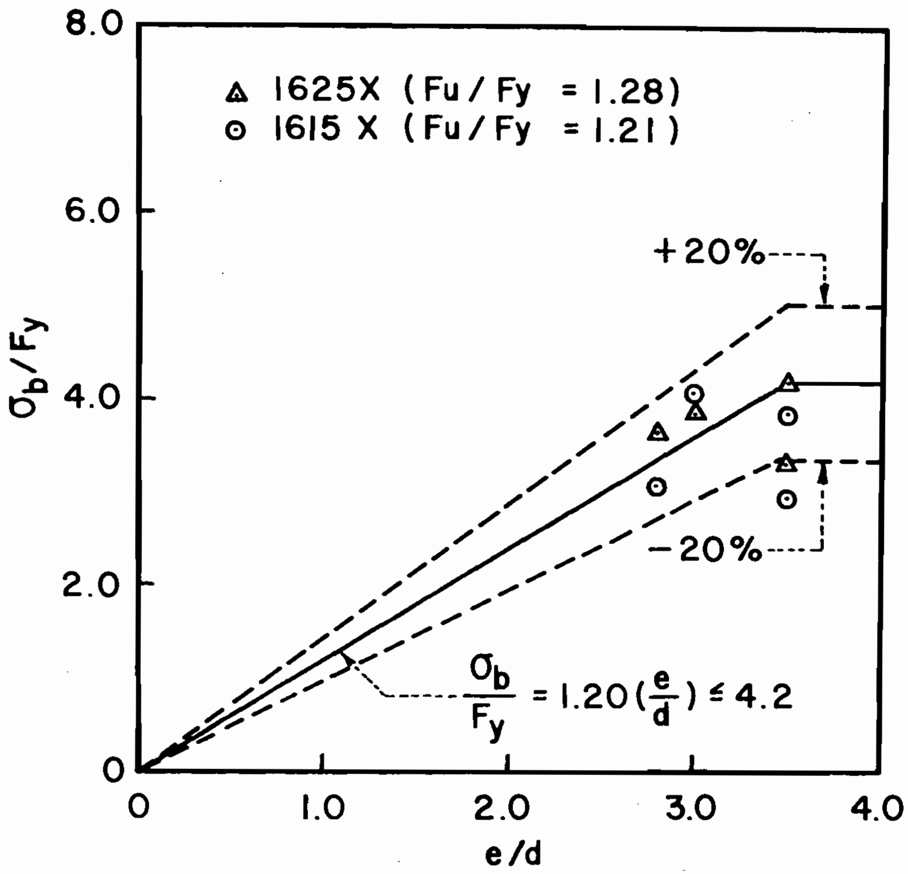

Fig. 2 Effect of Ductility ($F_u/F_y \simeq 1.25$)[6]

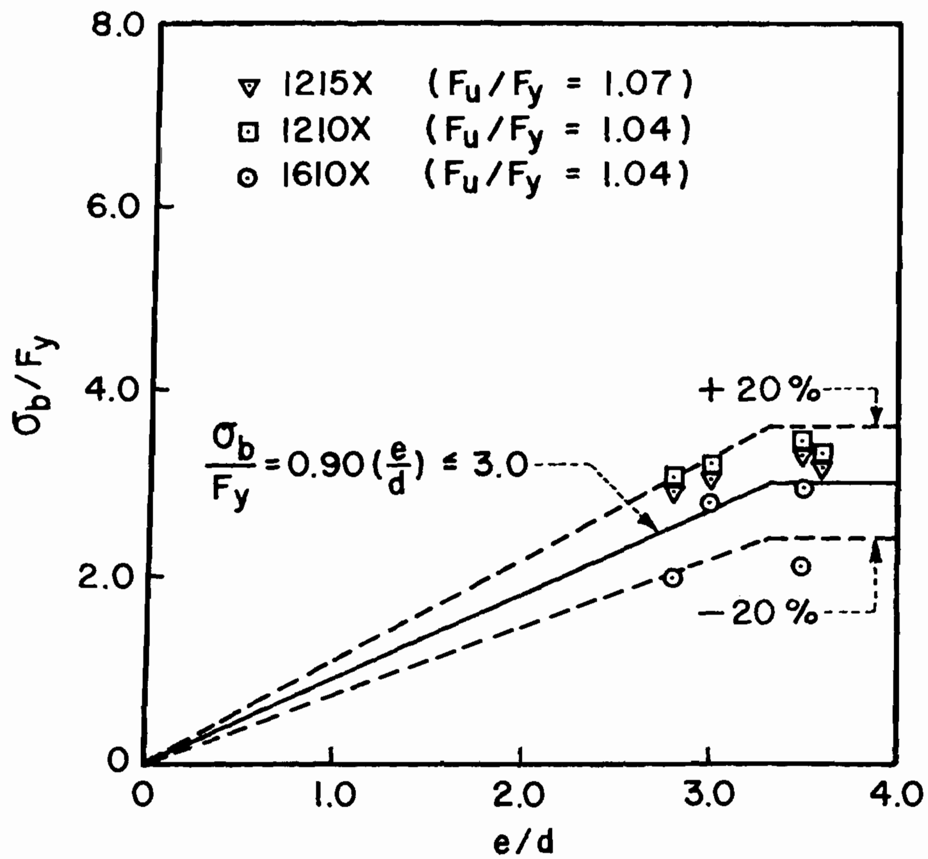

Fig. 3 Effect of Ductility ($F_u/F_y \leq 1.1$)[6]

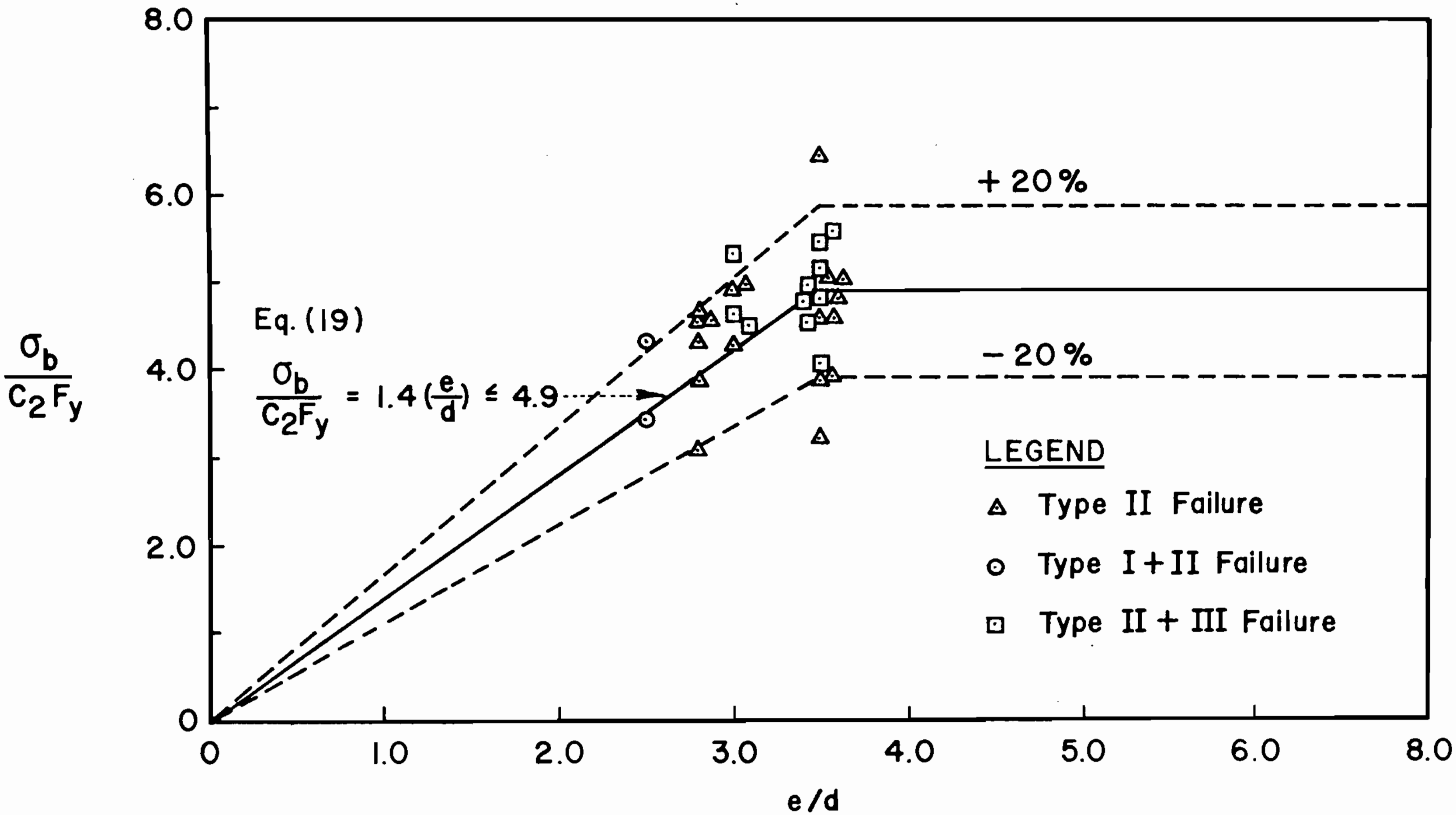

Fig. 4 Effect of C_2 Factor (Combination of the Test Data Shown in Figs. 1, 2 and 3)[6]

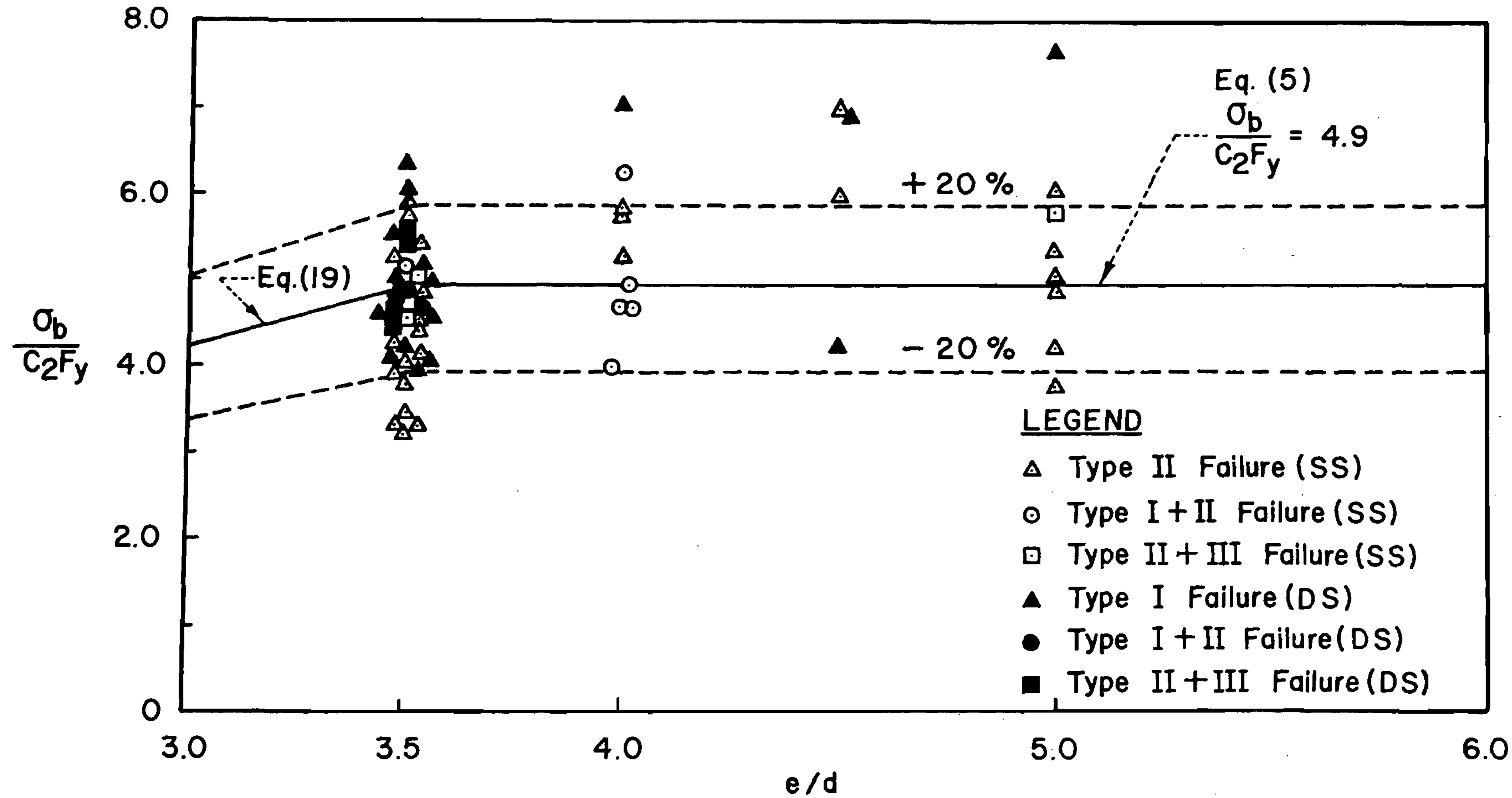

Fig. 5 Effect of Single and Double Shear Connections on Bearing Strength [9,10]

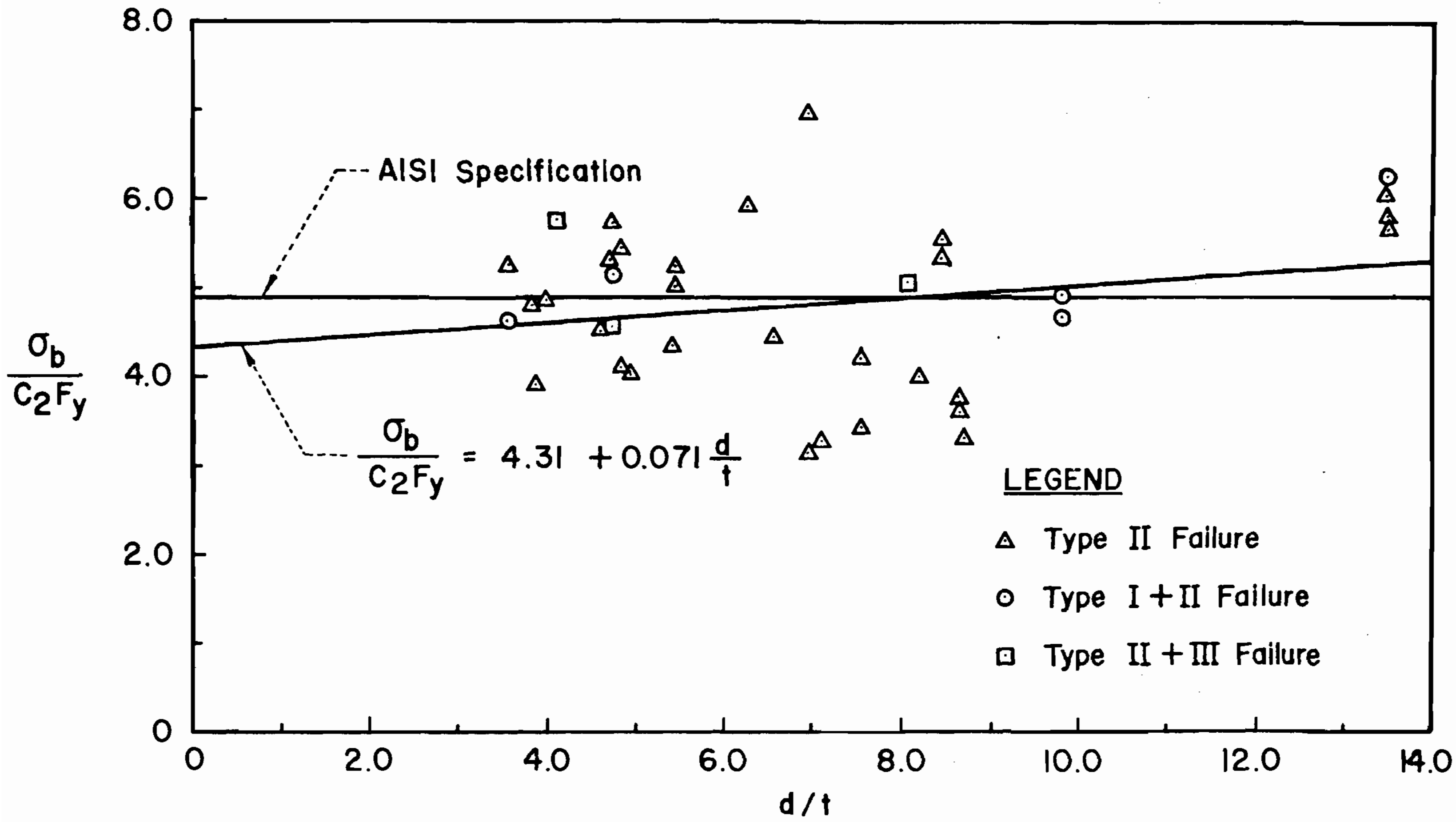

Fig. 6 Effect of d/t Ratio on Bearing Strength (Single Shear)[6,7,9,10,14]

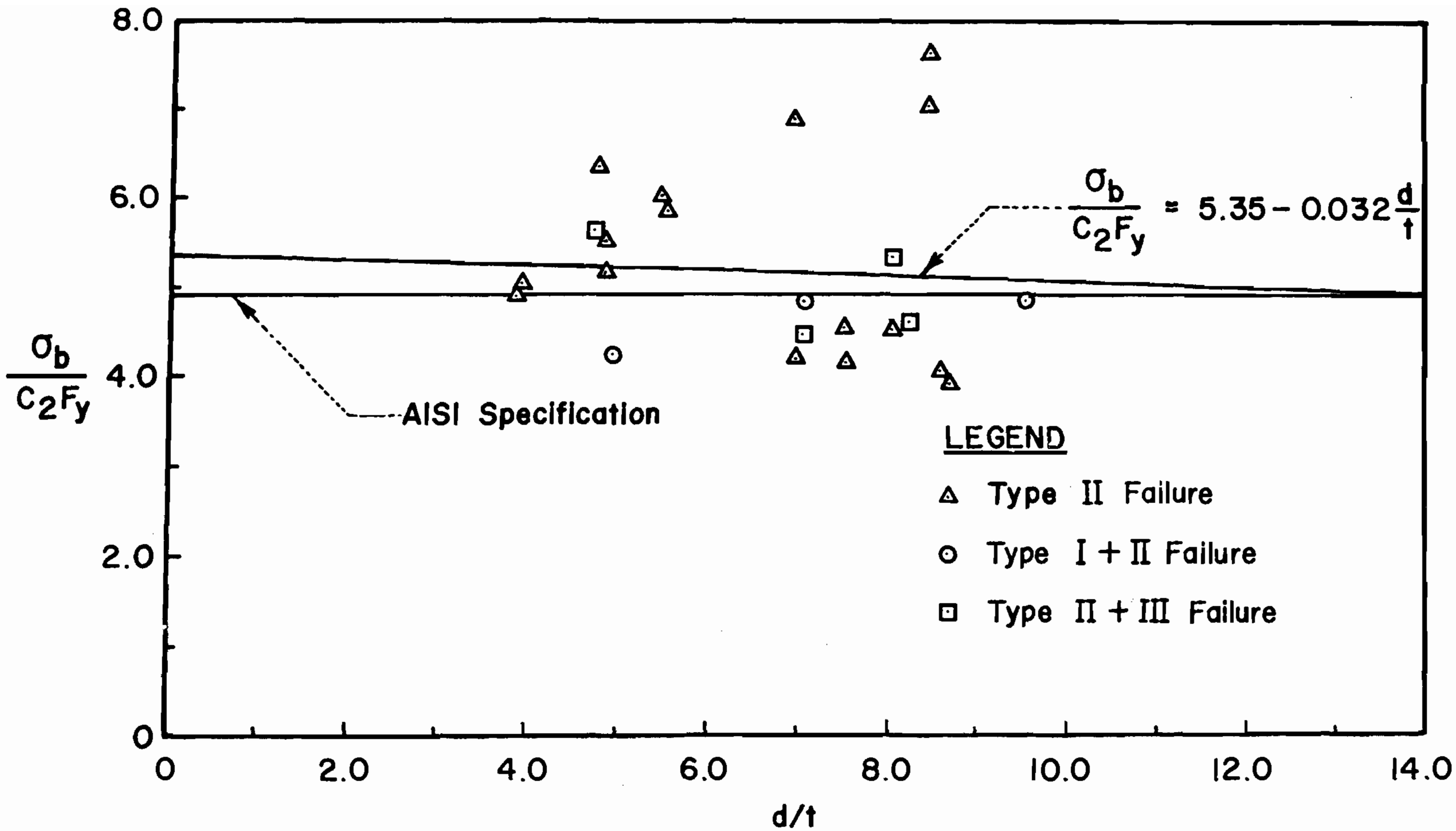

Fig. 7 Effect of d/t Ratio on Bearing Strength (Double Shear)[6,9,10,14]

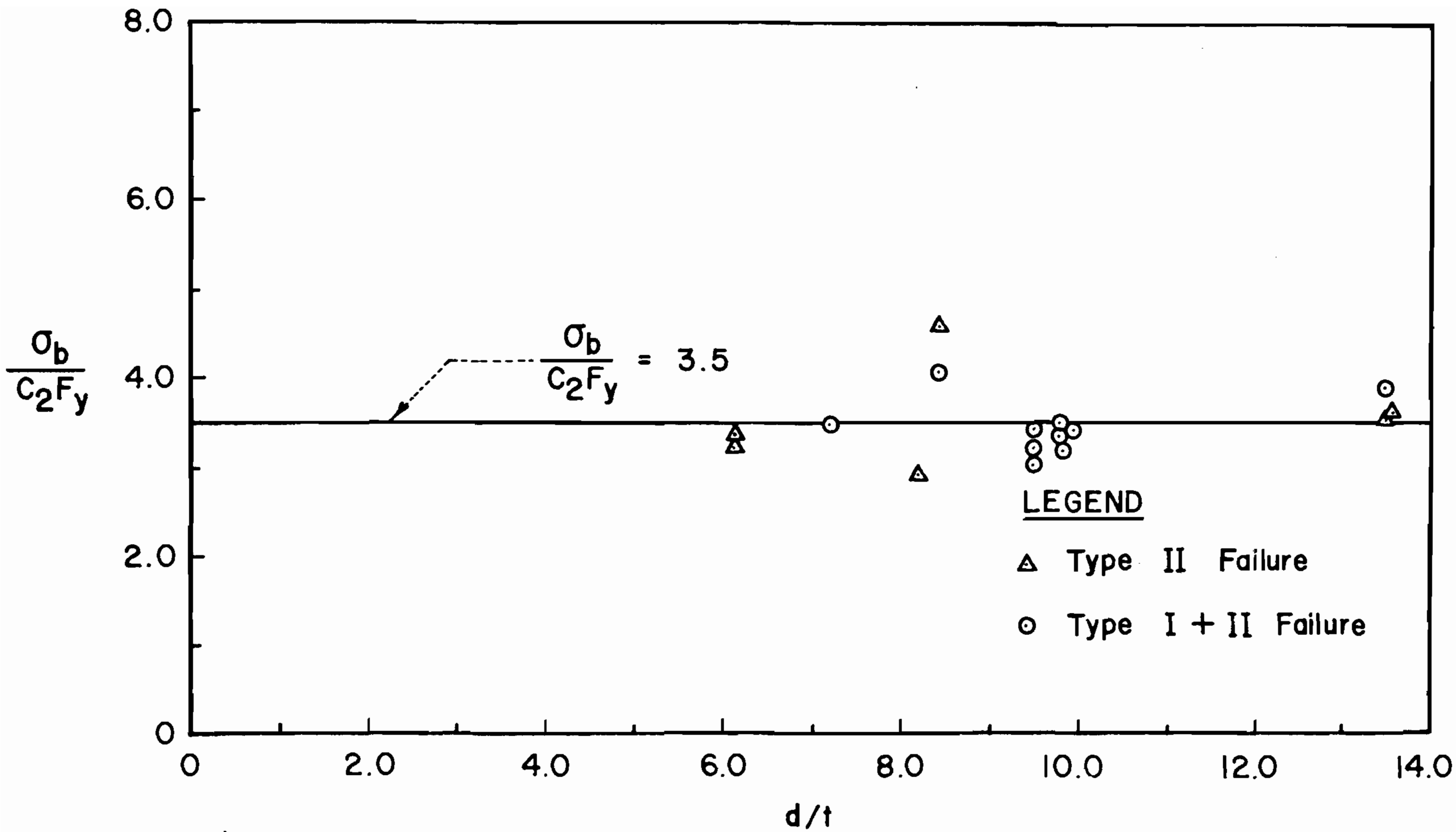

Fig. 8 Effect of d/t Ratio on Bearing Strength of Connections without Washers (Single Shear)[7]

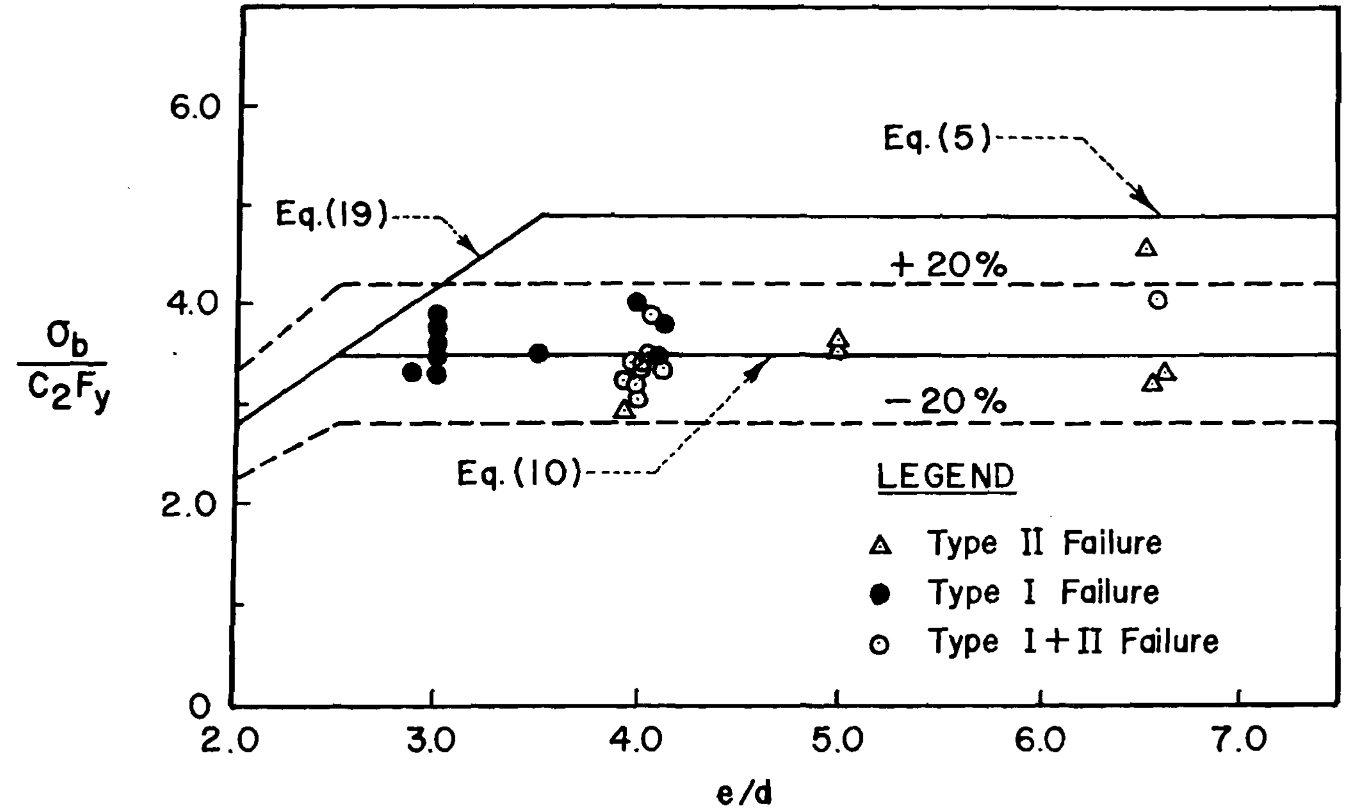

Fig. 9 Effect of e/d on Bearing Strength of Bolted Connections without Washers[7]

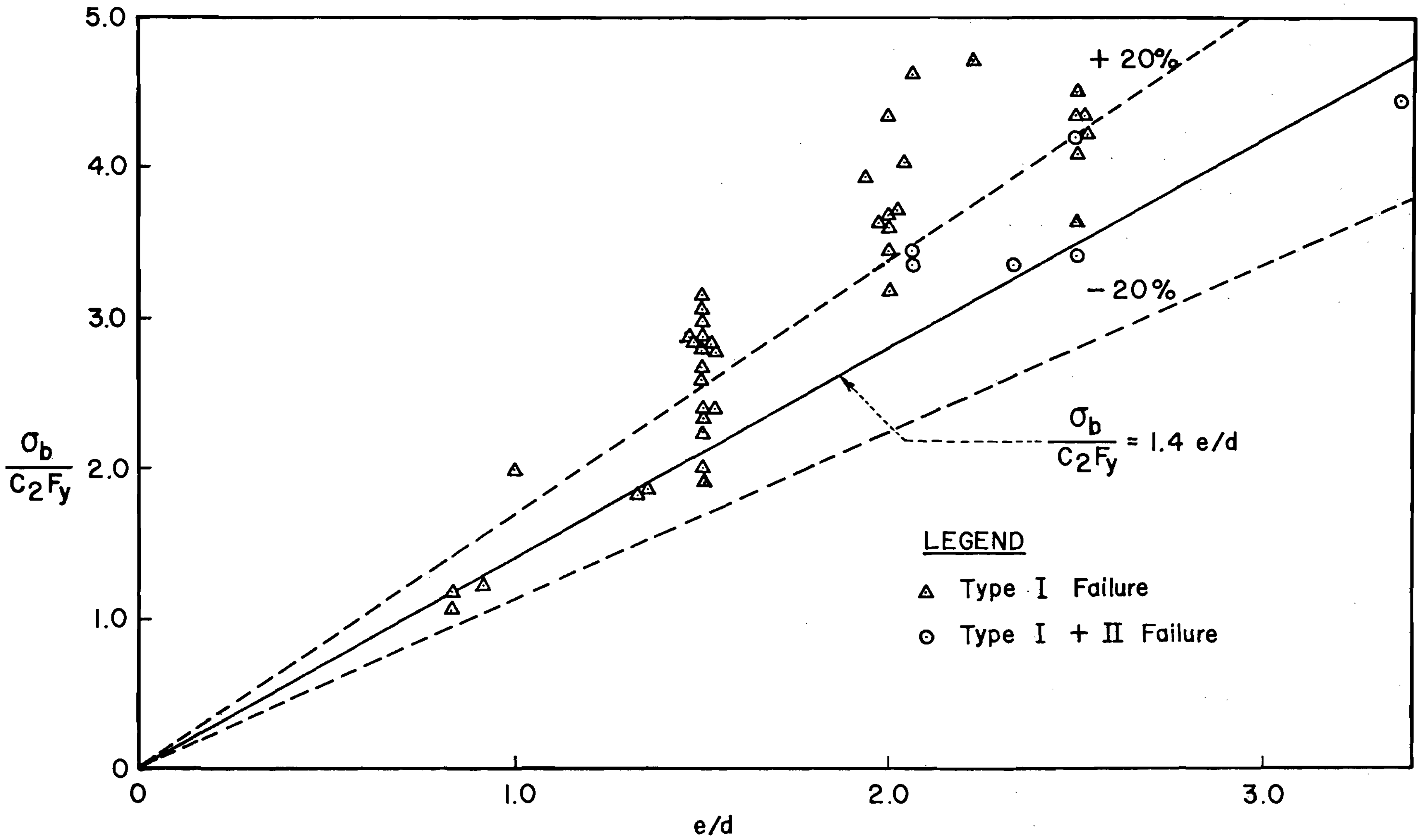

Fig. 10 Effect of e/d on Longitudinal Shear Strength of Steel Sheets (Single Shear)[6,7,9,10,14]

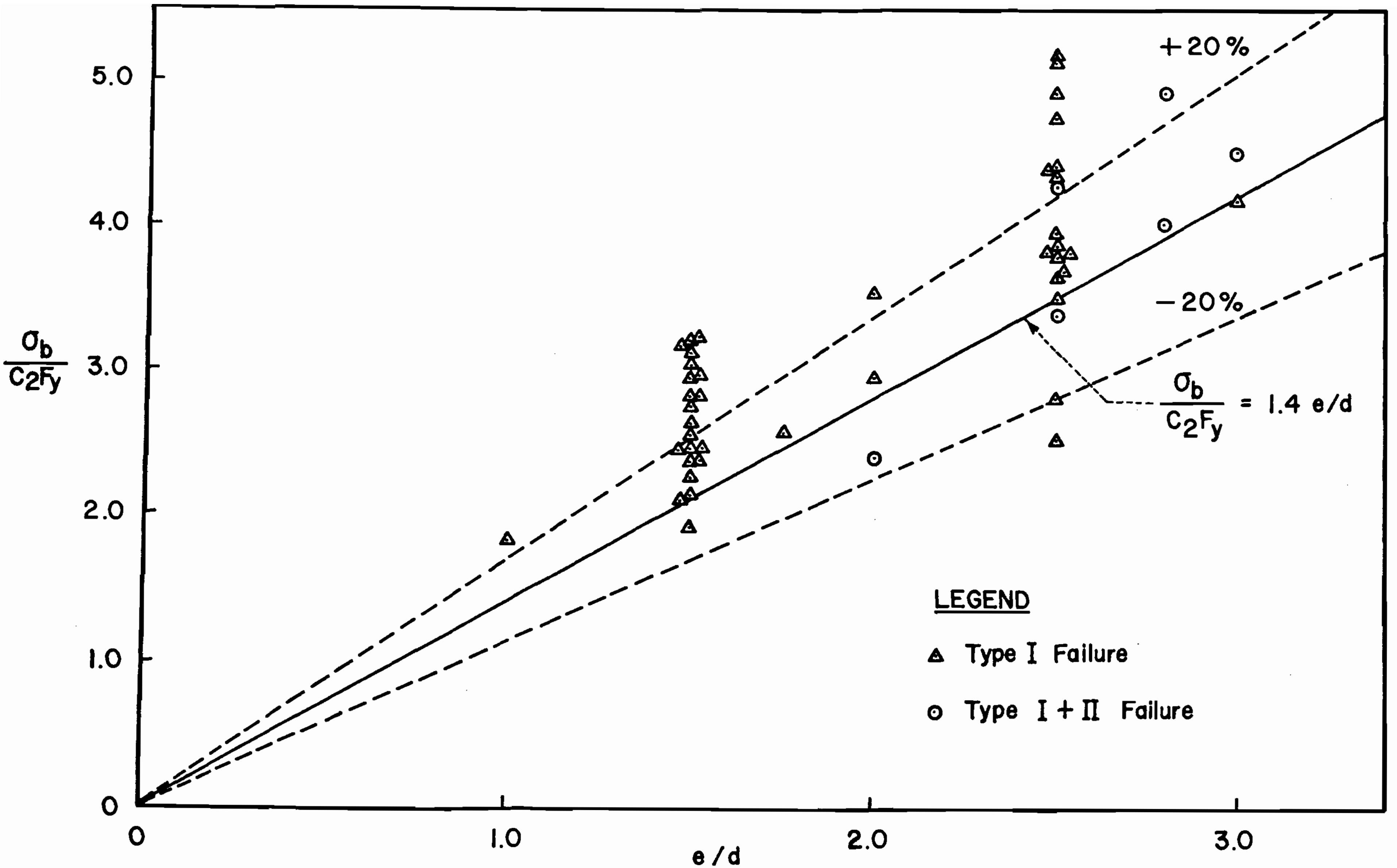

Fig. 11 . Effect of e/d on Longitudinal Shear Strength of Steel Sheets (Double Shear)[6,9,10]

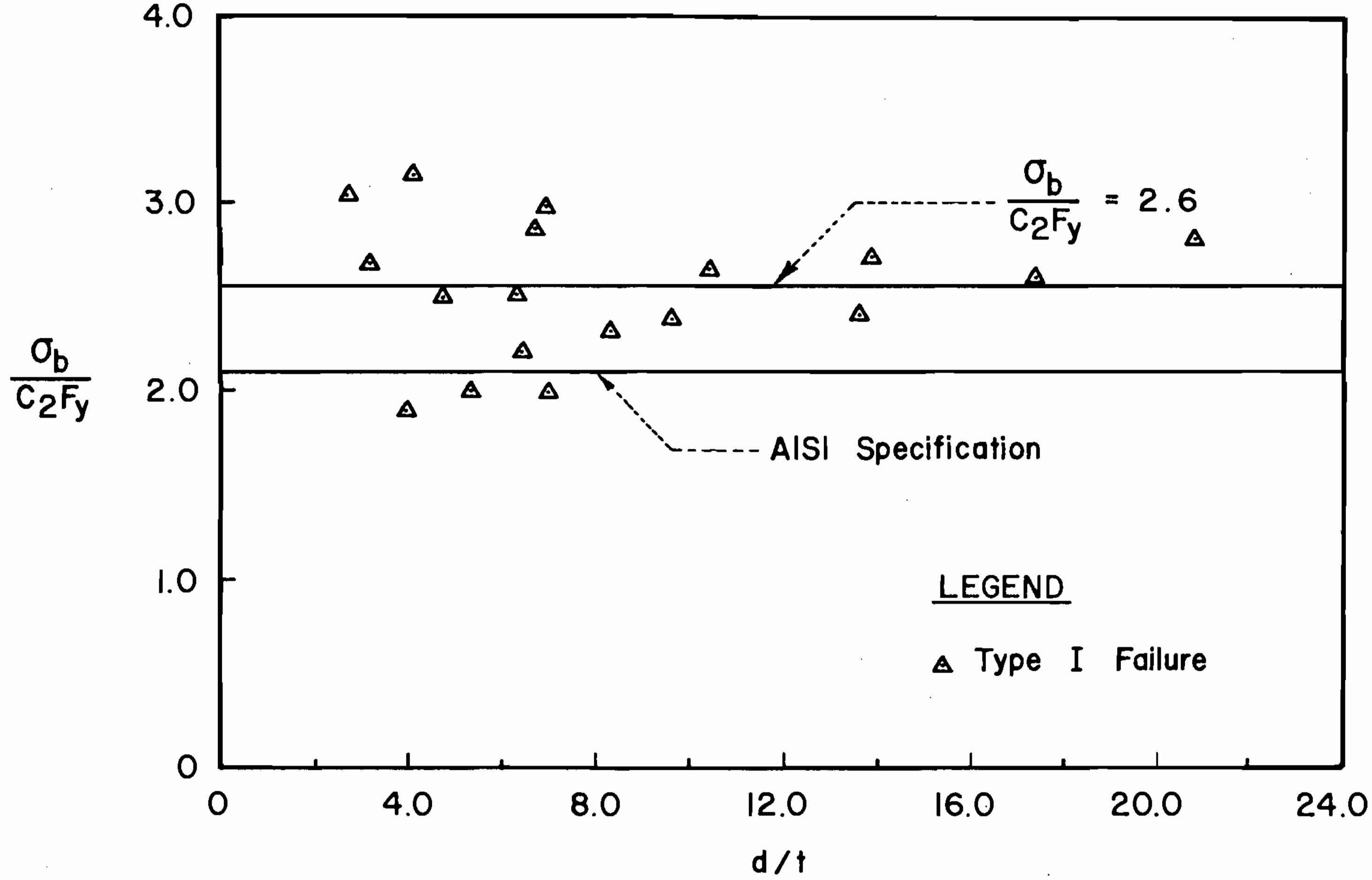

Fig. 12 Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Single Shear, e/d = 1.5)[9,10]

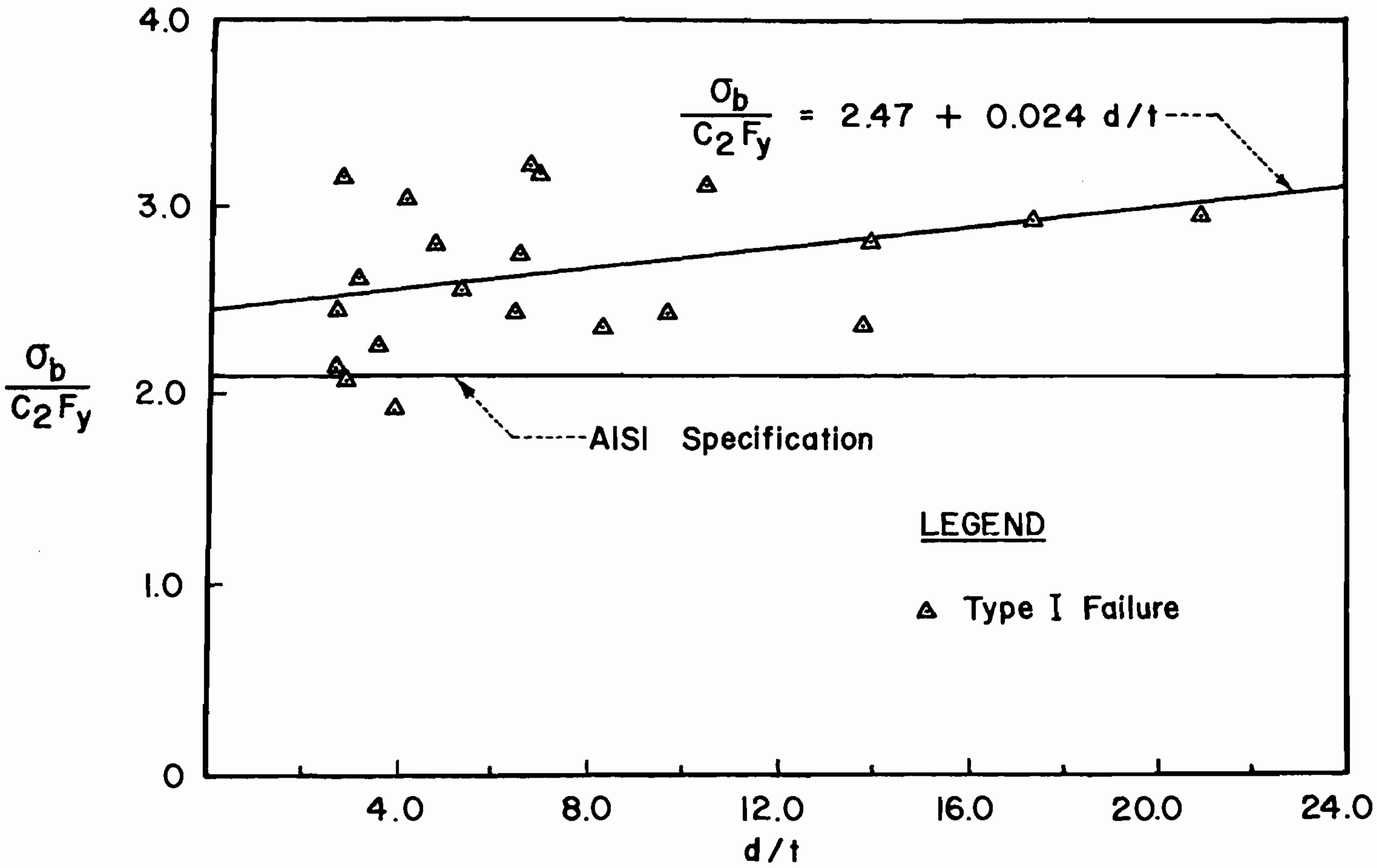

Fig. 13 Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Double Shear, e/d = 1.5)[9,10]

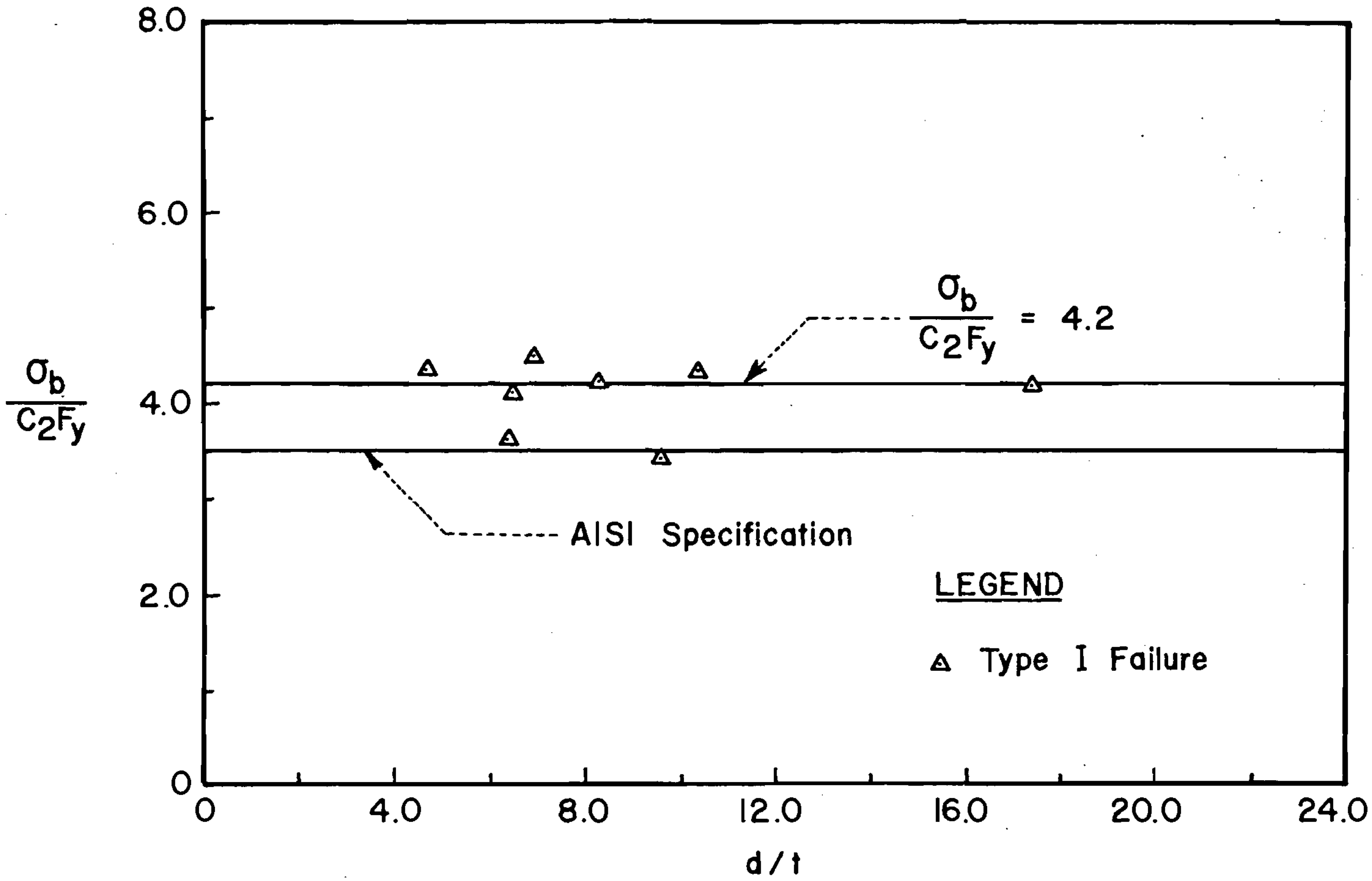

Fig. 14 Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Single Shear, e/d = 2.5)[9,10]

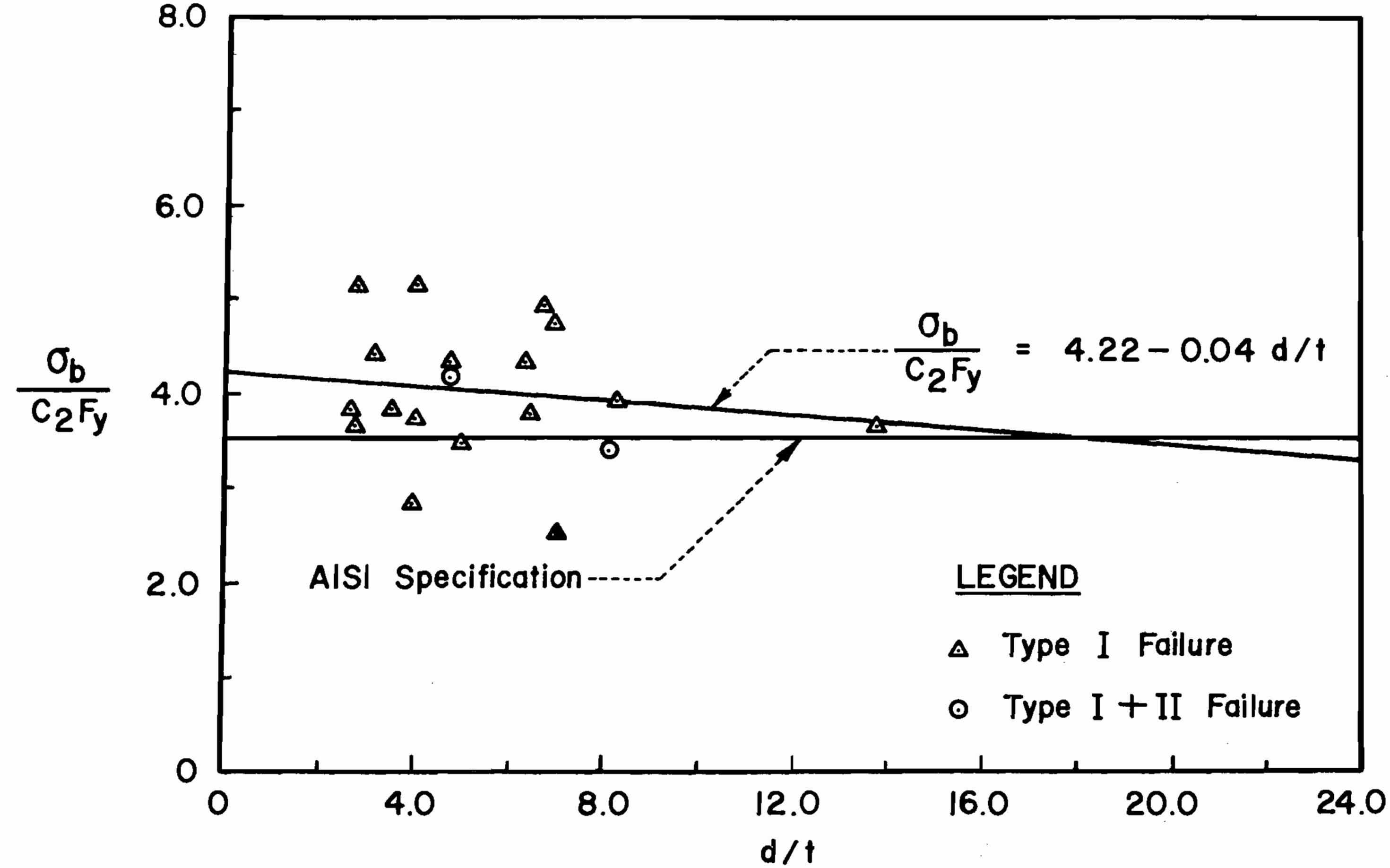

Fig. 15 Effect of d/t on Lonitudinal Shear Strength of Steel Sheets (Double Shear e/d = 2.5)[6,9,10]

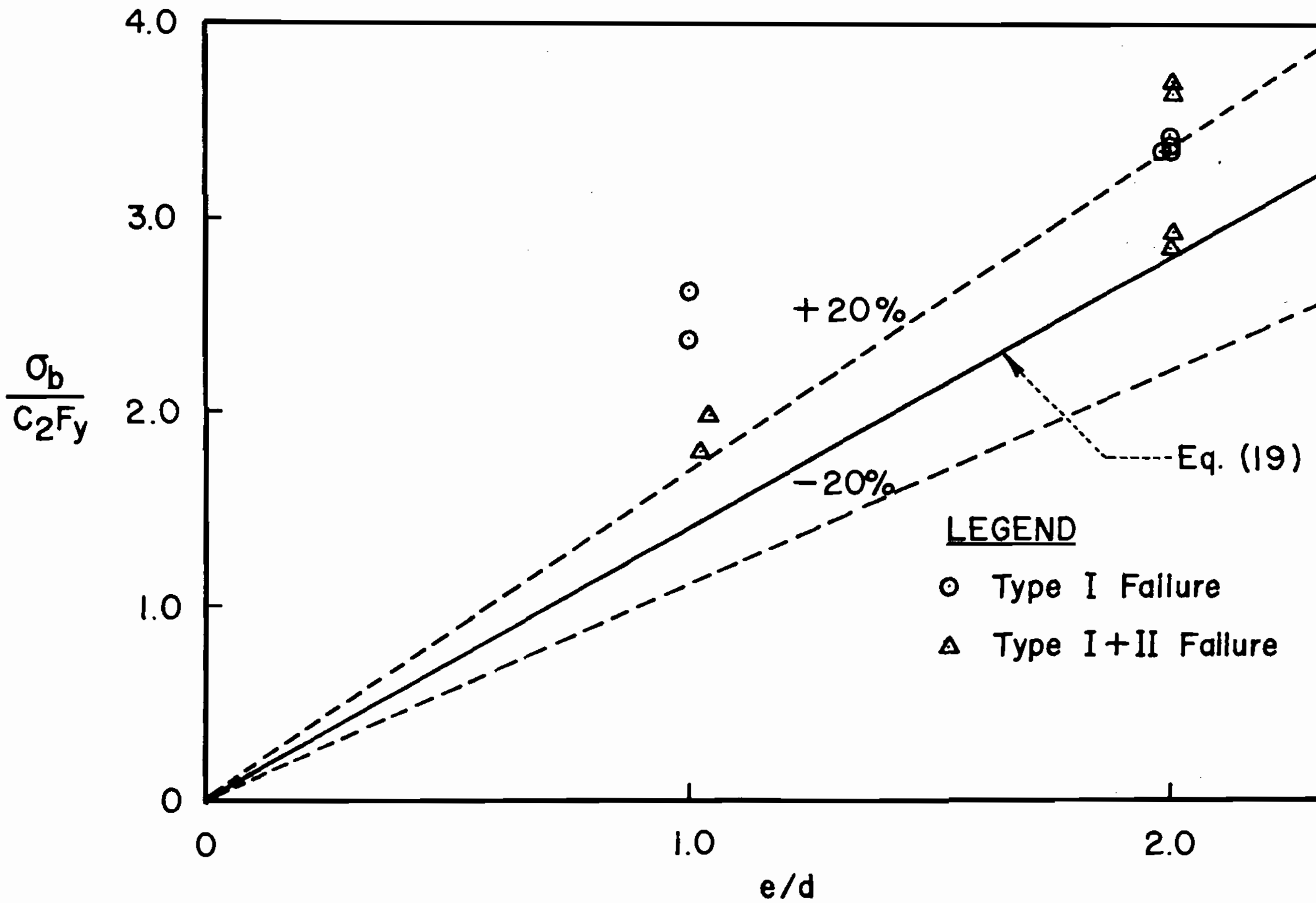

Fig. 16 Effect of e/d on Longitudinal Shear Strength of Steel Sheets in Bolted Connections without Washers[7]

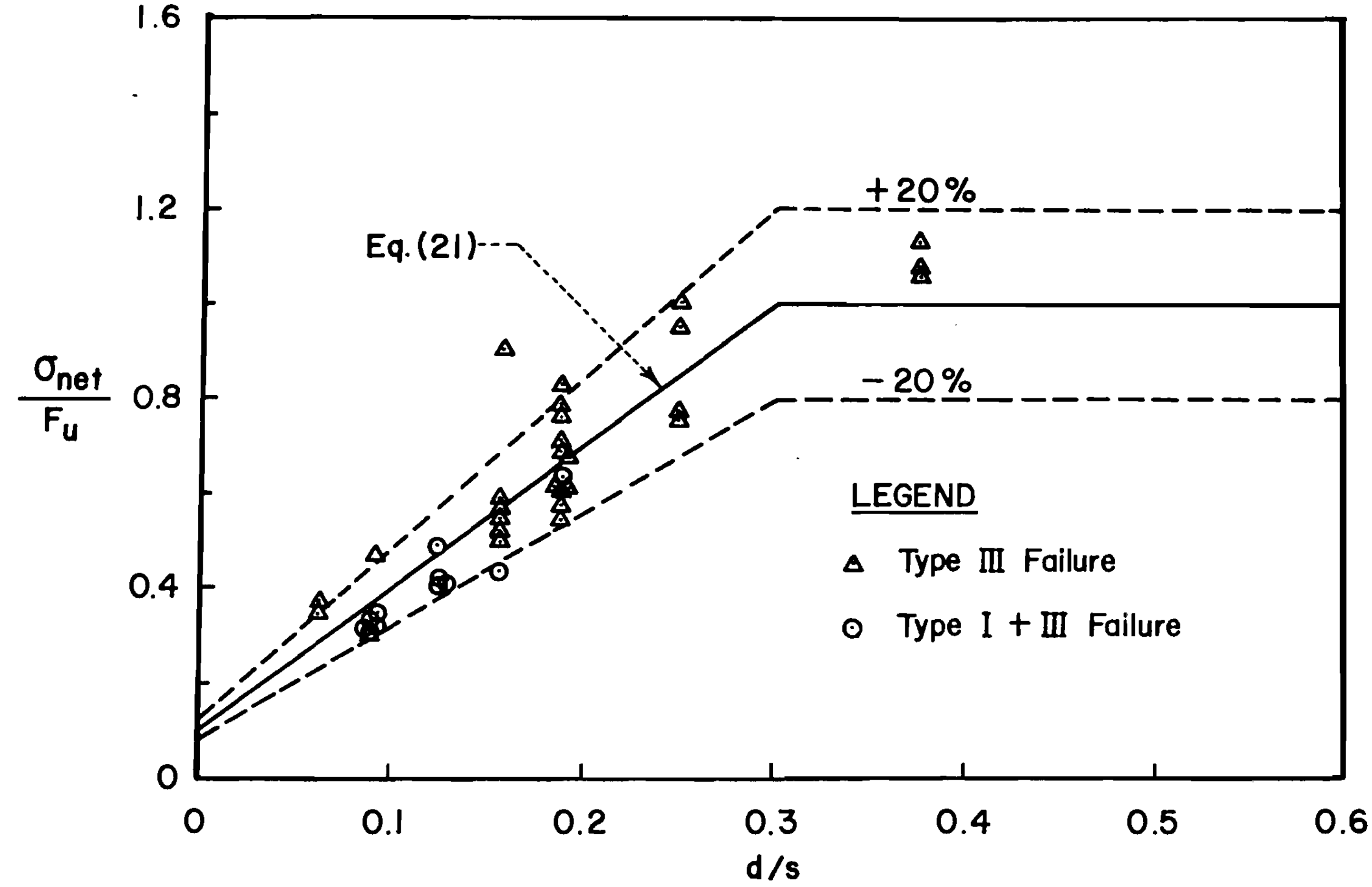

Fig. 17 Effect of d/s on Tensile Strength of Bolted Connections Using High Ductility Steels (Single Shear, One Bolt)[9,10]

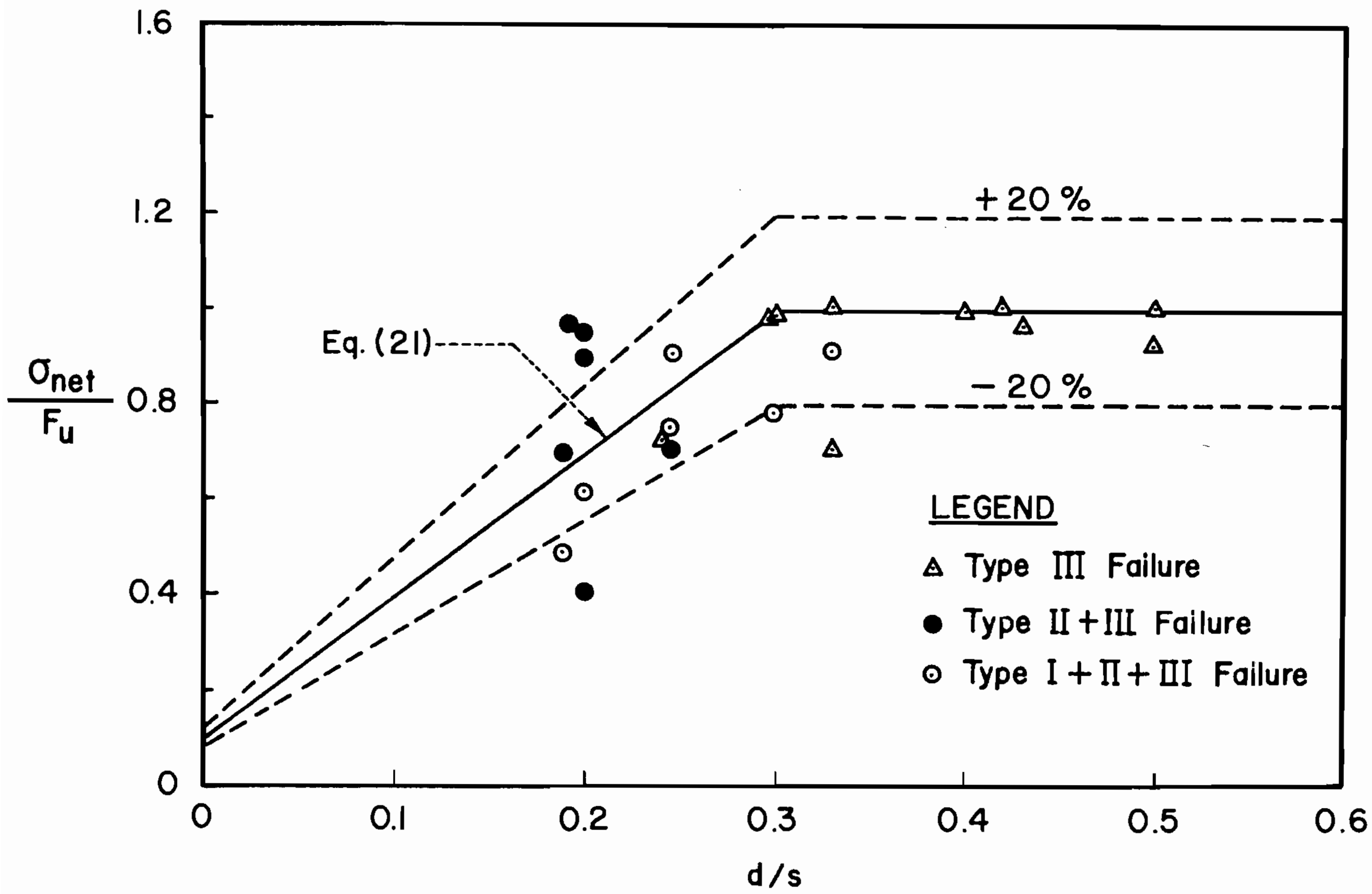

Fig. 18 Effect of d/s on Tensile Strength of Bolted Connections Using Low Ductility Steels (Single Shear, One Bolt)[6]

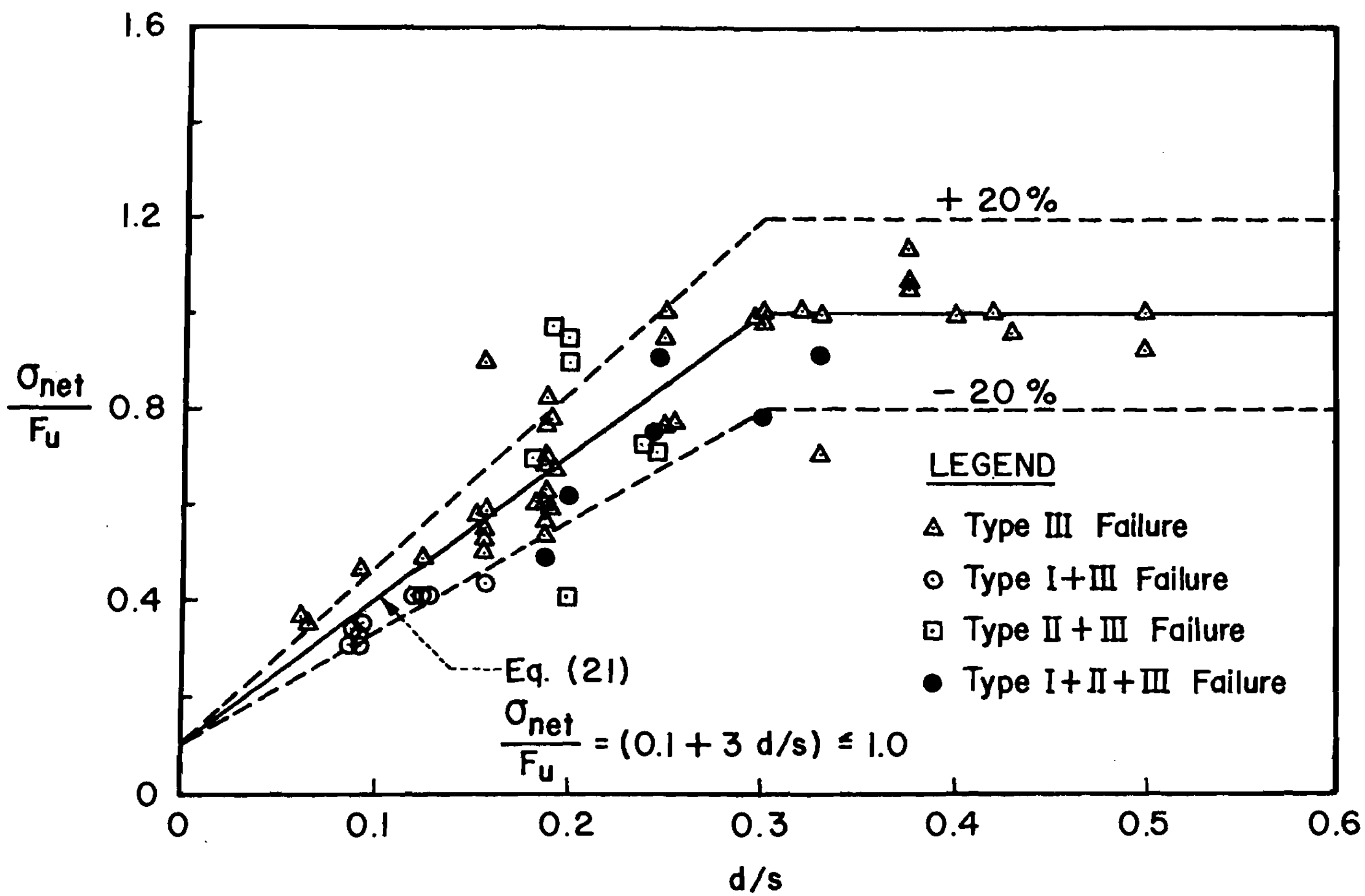

Fig. 19 Effect of d/s on Tensile Strength of Bolted Connections (Combination of the Data Shown in Figs. 17 and 18) (Single Shear, One Bolt)[6,9,10]

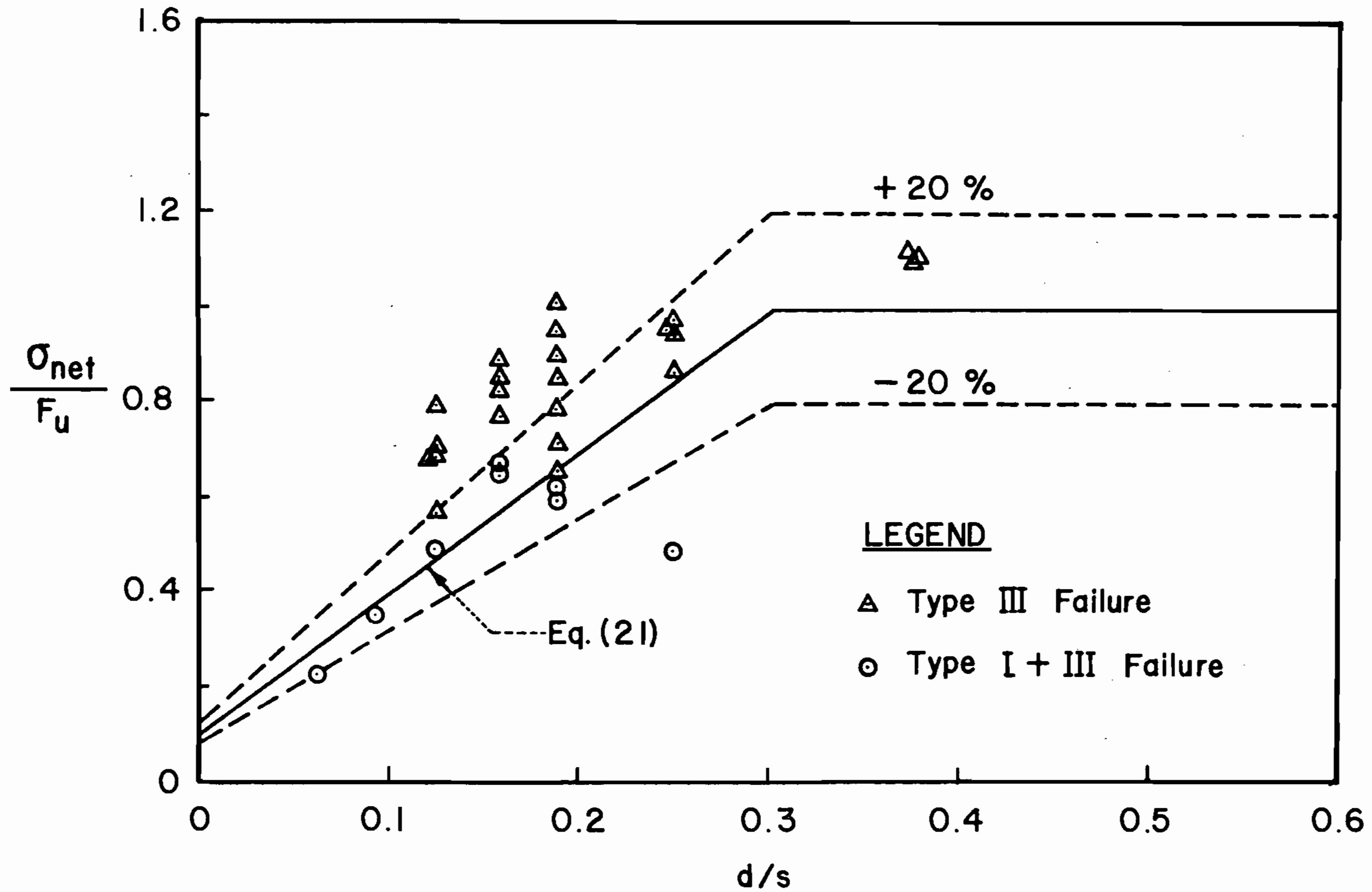

Fig. 20 Effect of d/s on Tensile Strength of Bolted Connections Using High Ductility Steels (Double Shear, One Bolt)[9,10]

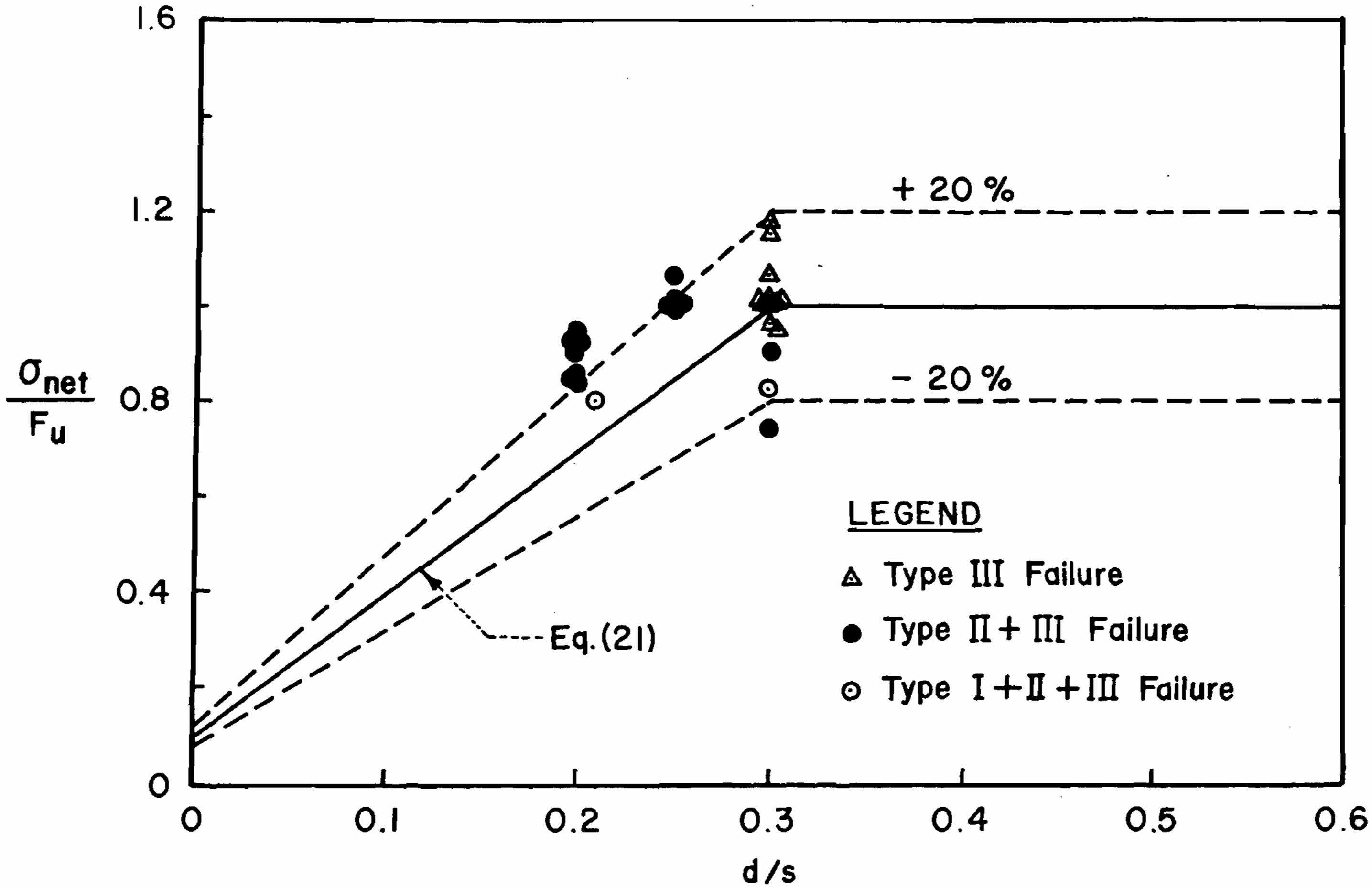

Fig. 21 Effects of d/s on Tensile Strength of Bolted Connections Using Low Ductility Steels (Double Shear, One Bolt)[6]

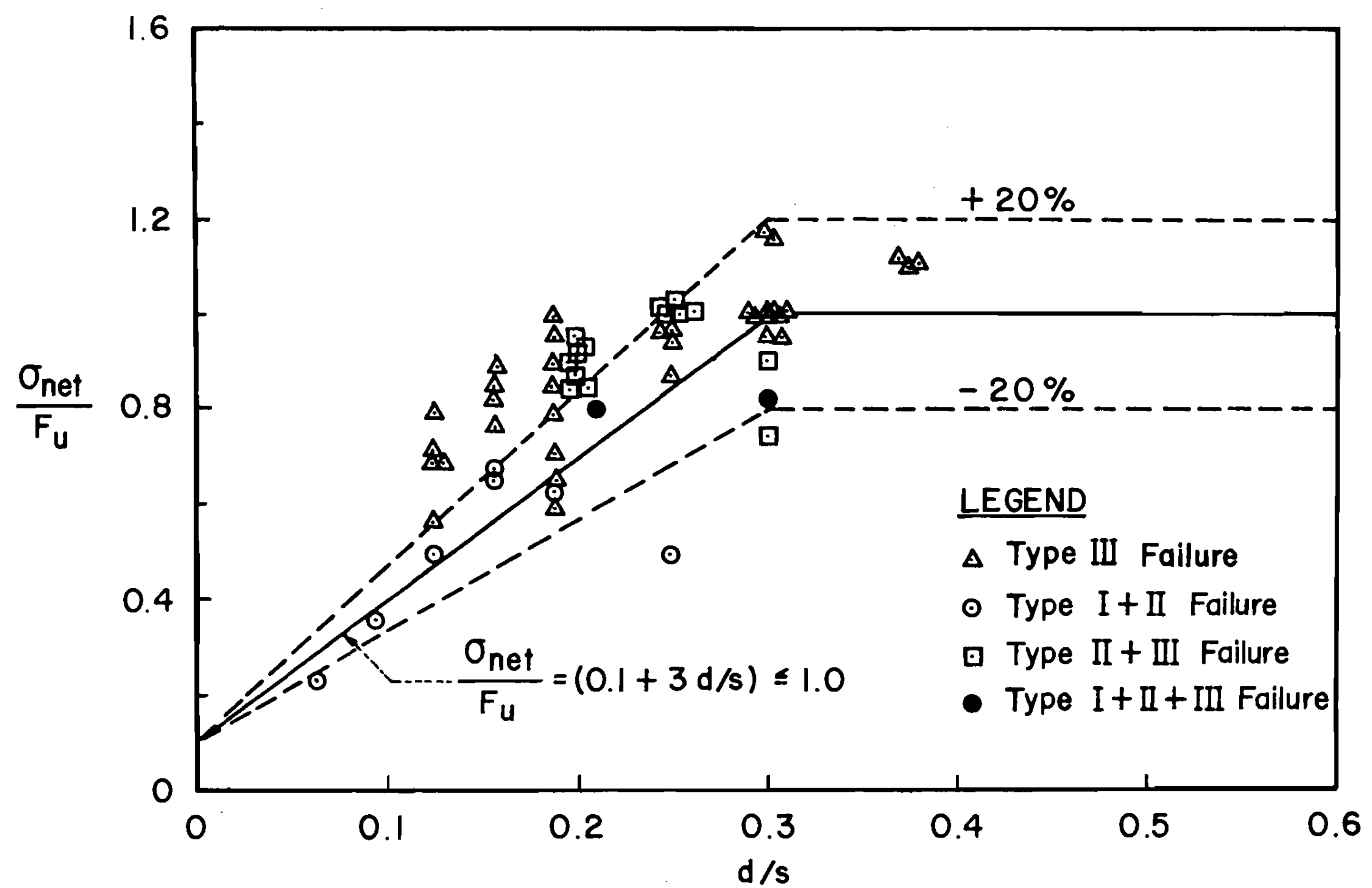

Fig. 22 Effect of d/s on Tensile Strength of Bolted Connections (Combination of the Data Shown in Figs. 20 and 21) (Double Shear, One Bolt)[6,9,10]

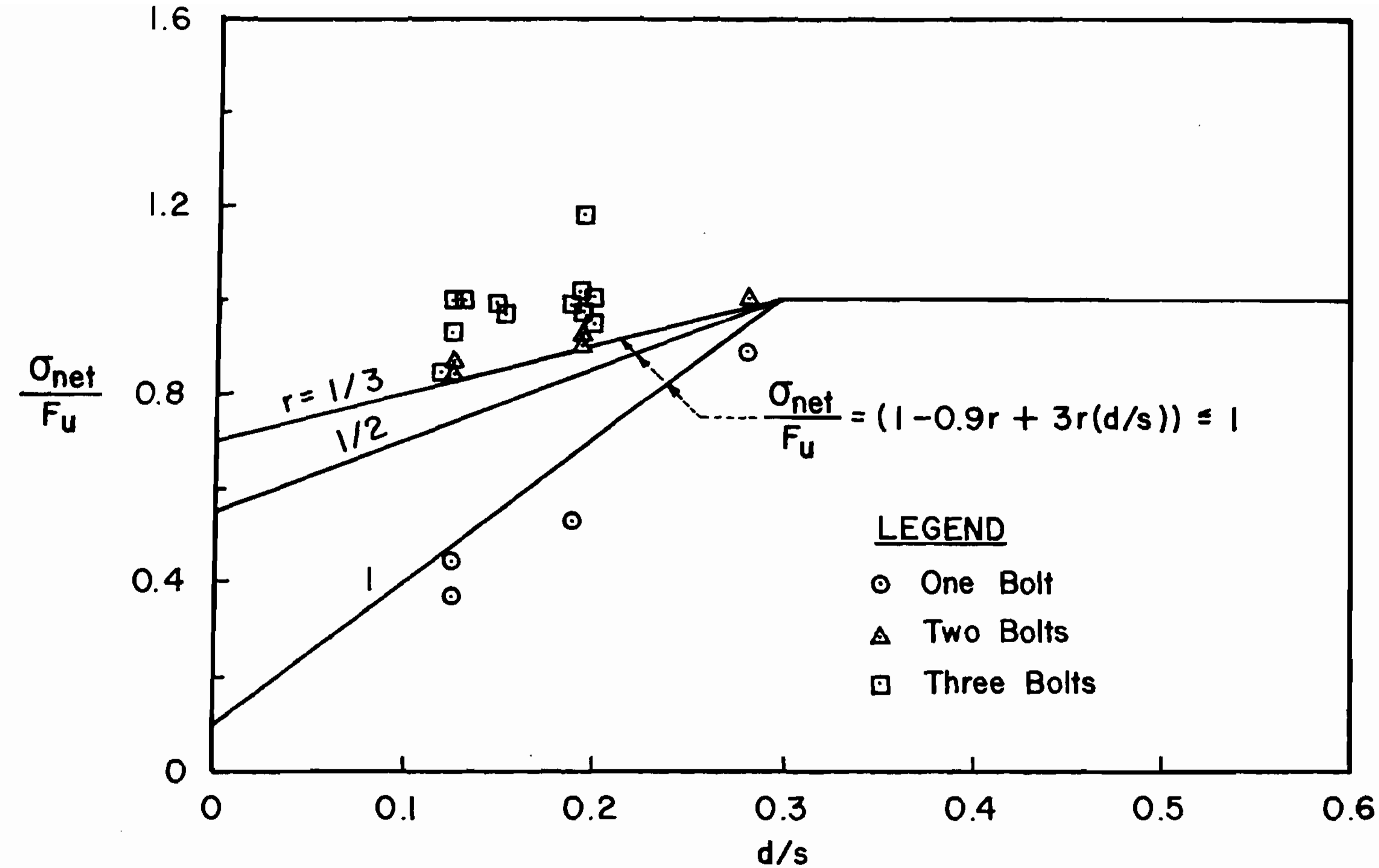

Fig. 23 Effect of d/s on Tensile Strength of Bolted Connections (Single Shear, Multi-Bolt)[5]

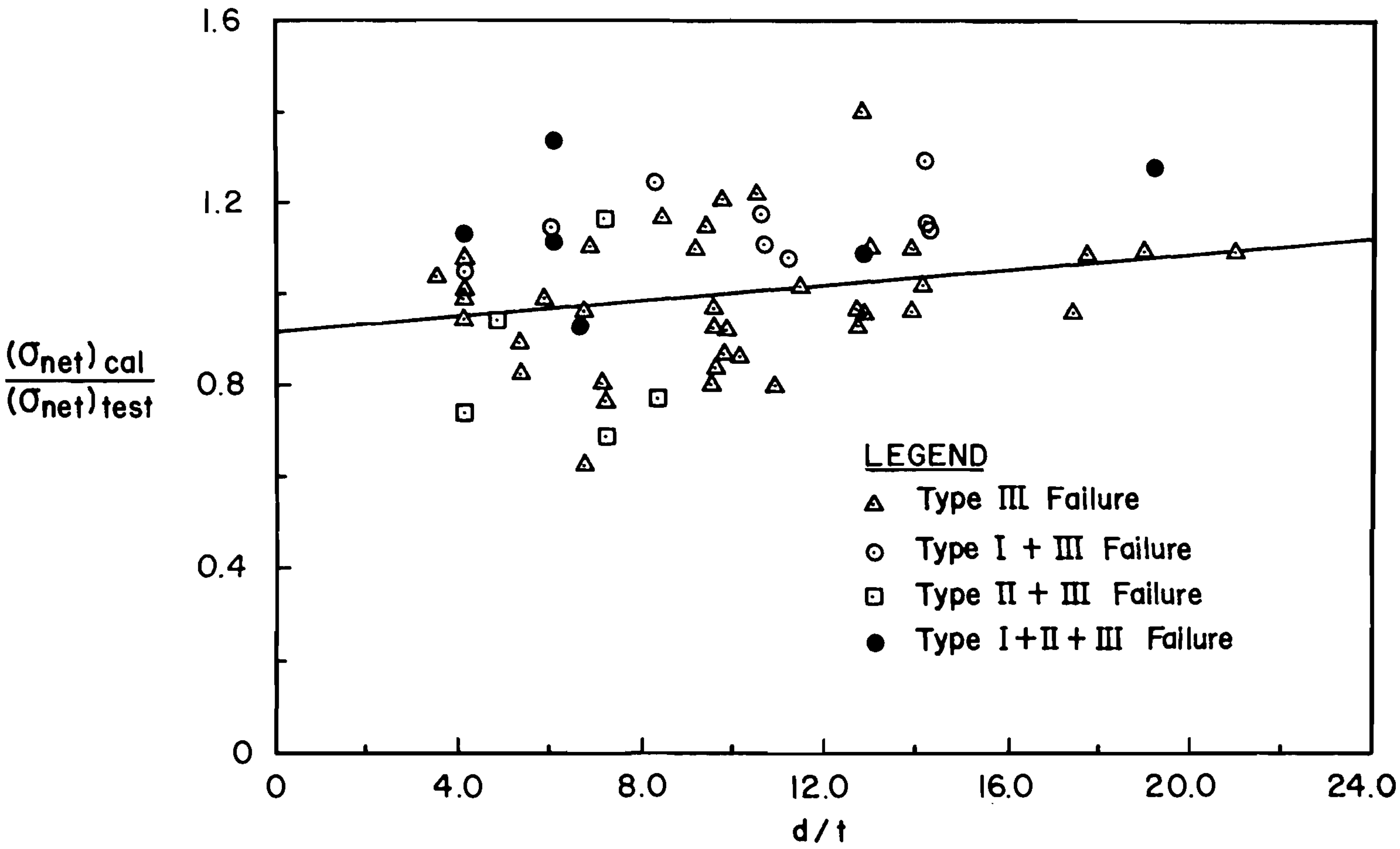

Fig. 24 Effect of d/t on Tensile Strength of Bolted Connections (Single Shear)[6,9,10]

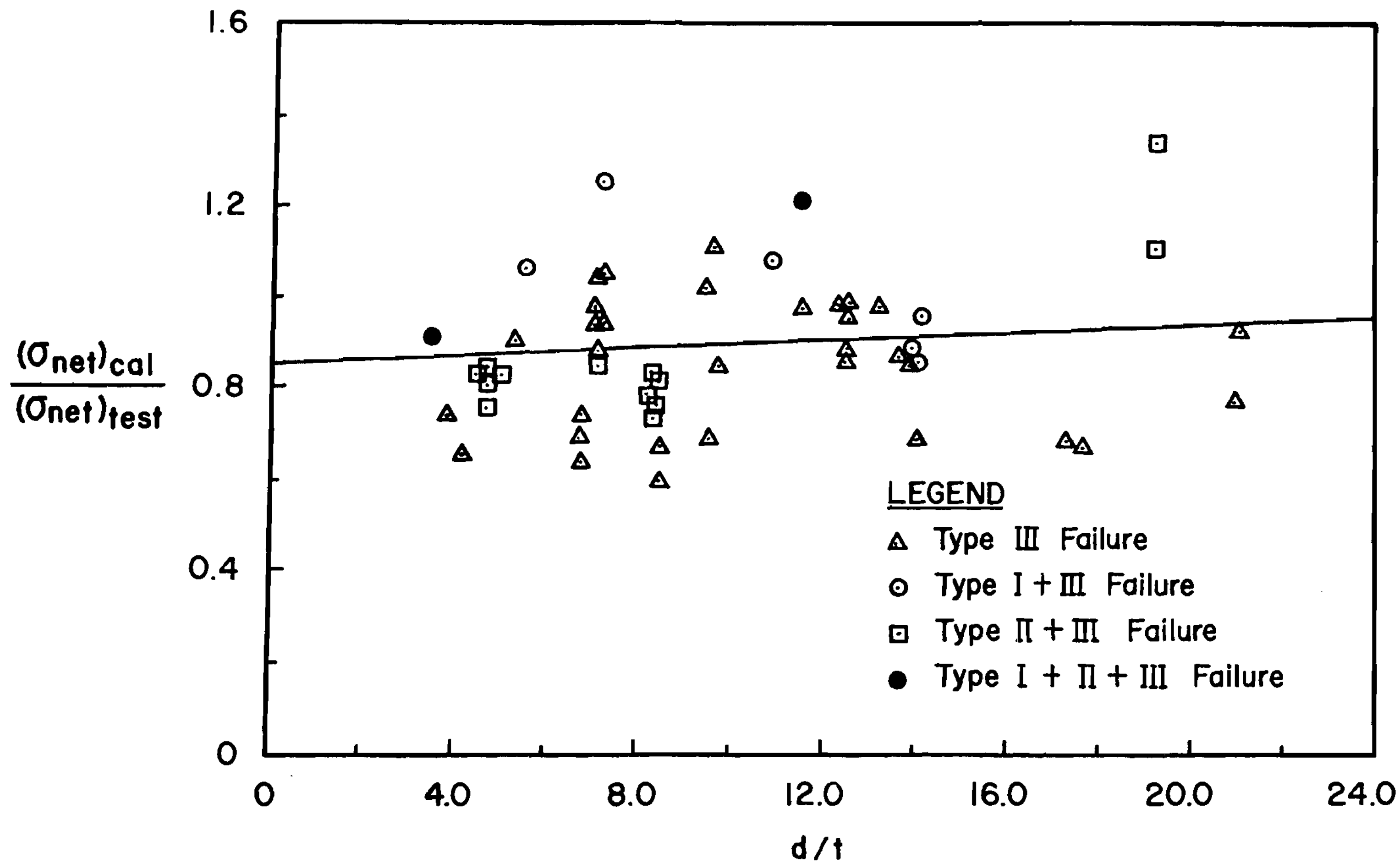

Fig. 25 Effect of d/t on Tensile Strength of Bolted Connections (Double Shear, One Bolt)[6,9,10]

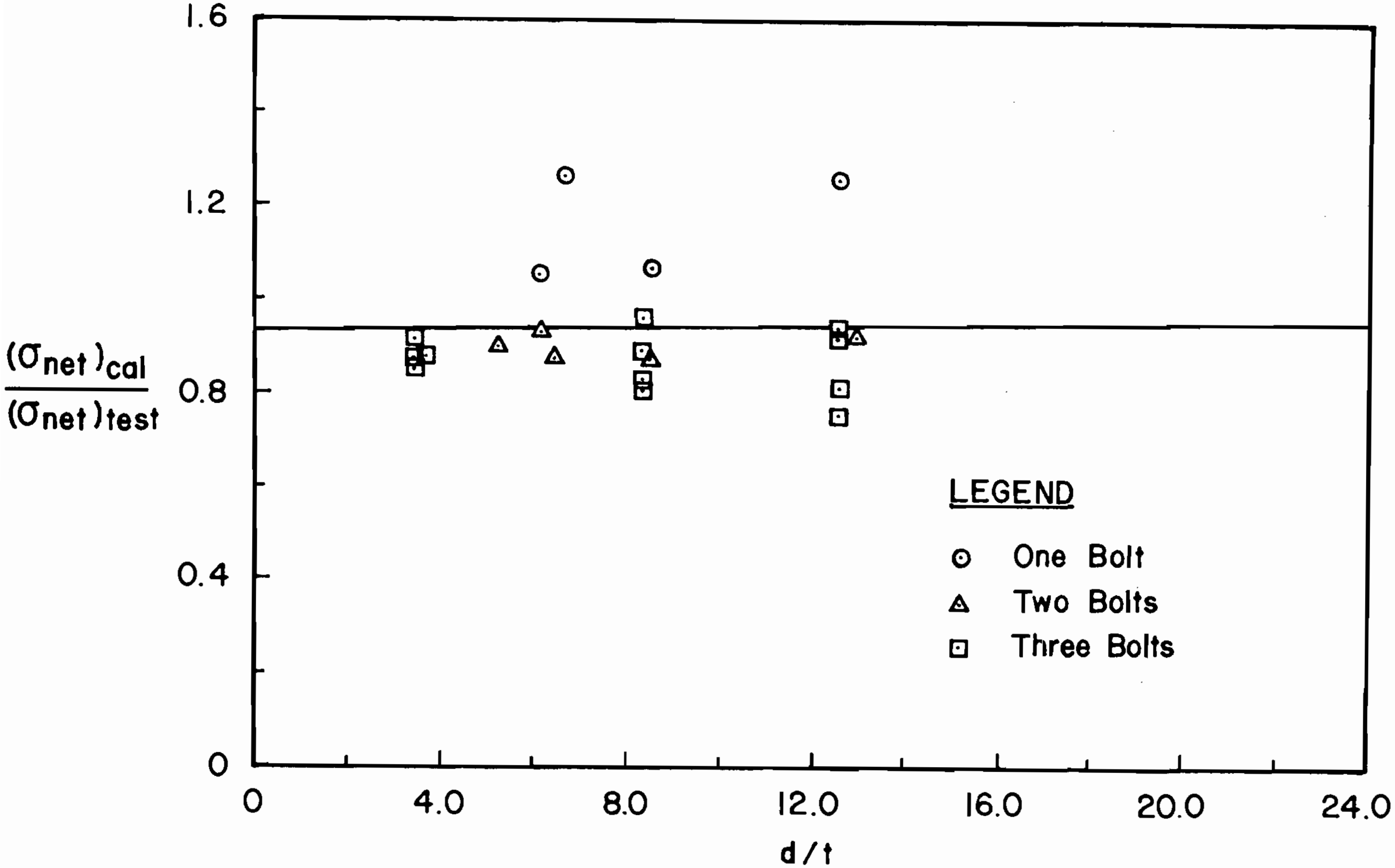

Fig. 26 Effect of d/t on Tensile Strength of Bolted Connections (Single Shear, Multi-Bolt)[5]

Department of Civil Engineering

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SECOND PROGRESS REPORT

BOLTED CONNECTIONS IN COLD-FORMED STEEL STRUCTURES

by

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A Research Project Sponsored by

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PREFACE

In June 1976, the First Progress Report on Bolted Connections in Cold-Formed Steel Structures was submitted to American Iron and Steel Institute. It summarized the available test data and studied the applicability of the present design formulas for bolted connections. During the Summer, 1976 two types of investigations were conducted at the University of Missouri-Rolla. The first dealt with an evaluation of bolt tension induced by the applied torque during installation. The second involved a preliminary study of the effects of washers and torque on the bearing strength of connections composed of steel sheets thinner than 0.036 in. This report presents the results of these investigations.

The planned future study on bolted connections will consist of a study of the effect of bolt installation on the bearing capacity of the connections. The parameters to be used in the future study are based on the recommendations of the AISI Task Group formulated at its September 15, 1976 meeting.

This research project was sponsored by American Iron and Steel Institute. The technical guidance provided by the AISI Task Group on bolted connections (Mr. L.W. Ife, Chairman, Messrs. T.J. Jones, and D.S. Wolford, members) and the AISI staff (Dr. A.L. Johnson and Mr. D.P. Cassidy) is gratefully acknowledged. Thanks are also due to Mr. E.B. Gibson, former Chairman of the AISI Task Group and Mr. R.B. Matlock, former member of the Task Group, for their technical guidance.

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I. BOLT INSTALLATION

A. Introduction

The development of Section 4.5 of the 1968 Edition of the AISI Specification for the Design of Cold-Formed Steel Structural Members[1] is based primarily on the study made at Cornell University.[2,3,4,5,6,7,8] The bolted connection specimens tested in this study were assembled with the same torques throughout the testing program. The torque values used are shown in Tables 1 and 2 for A307 bolts and A325 high strength bolts, respectively. Also these same torque values were used in the recent studies made by Chong and Matlock[9], Victor Liu[10] and Haussler[11].

When the AISI Specification is compared with the Specification of the Research Council on Riveted and Bolted Structural Joints (RCRBSJ),[12] the current AISI Specification does not provide the exact procedure to be followed for the installation of bolted connections. For high-strength structural bolts, RCRBSJ specifies that the bolts must be tightened so that the resulting bolt tension is at least 70% of the specified minimum tensile strength. The required minimum bolt tension is given in the RCRBSJ Specification, as listed in Table 3. These values are achieved by using calibrated wrenches, the turn-of-nut method, or direct tension indicators.

When high-strength bolts were first introduced, installation was primarily controlled by torque. Recent tests show that there is a great variability of the torque-tension relationship,[13] which is one reason why the present RCRBSJ Specification for bolted connections requires a specific minimum bolt tension instead of torque. Also, it has been noted that for steel structures using hot rolled shapes connections can be designed as either friction-type or bearing type when high-strength bolts are used. However, in cold-formed steel construction only bearing-type connections are used. Therefore, the pretension in bolts is less important than with conventional steel structures. For this reason, it has been found satisfactory in previous research work and practice to install bolts by using torque control.

It is the purpose of this investigation first to develop a turn-of-nut method for bolt connections composed of cold-formed steel and second to determine the bolt tension developed from the torque values used in the original Cornell study.

B. Experimental Investigation

1. Design of Test Specimens

To develop a turn-of-nut method, it was necessary to have a means of measuring the tension developed in the bolt as the nut was tightened. This was accomplished by using a specially designed load cell and a direct tension indicator.

Hollow steel cylinders mounted with four strain gages were used for the load cells. Figure 1 shows the steel cylinders for 1/2 and 5/8 inch diameter bolts. The dimensions are listed in Table 4. The cylinders were calibrated with a Tinius Oslen testing machine. The calibration curves for the load cells for 1/2 and 5/8 inch bolts are shown in Figure 2.

The direct tension indicator is a hardened washer with a series of protrusions on one face. The washer is inserted between the bolt head and the gripped material. The protrusions, which bear against the underside of the bolt head, leave a gap. When the bolt is tightened, the protrusions are flattened and the gap is reduced. Bolt tension is evaluated from measurements of the residual gap. The direct tension indicator and the procedure described above are illustrated in Figure 3. These washers are available for high strength 1/2 inch diameter bolts and larger. Table 5 lists the specified values of gap closure required for the minimum bolt tension.

To determine the relationship between bolt tension and the gap of the indicator, the test assembly shown in Figure 4 was used. As the nut was turned at specified angle increments, gap measurements and strain readings were recorded. From the calibration curves given in Figure 2, the bolt tension was then determined. The assembly shown in Figure 5 was used to obtain the relationship of gap versus nut rotation. By using the results obtained from the assembly of Figure 4, the relationship between the bolt tension and the required nut rotation was constructed for a given grip length. The relationships of bolt tension versus torque and torque versus nut rotation were also obtained from the tests.

The purpose of using the direct tension indicator and the load cells together was to provide a check for the experimental system described above. Favorable results were obtained from this procedure as discussed in Section I.B.3.

2. Testing of Specimens

Ten tests were conducted on 1/2 in. diameter A325 bolts. Five tests were run by using the assembly shown in Figure 4 and the remaining five tests were run by using the assembly shown in Figure 5. Table 6 lists the dimensions of the bolts used in the tests.

The tests performed on the 5/8 in. diameter bolts consisted of four tests for which the assembly shown in Figure 4 was used. For 11 tests, the assembly shown in Figure 5 was used. The effect of different grip lengths was studied in the 11 tests. Table 7 lists the dimensions of the bolts.

3. Test Results and Evaluation of Test Data

As described in the previous section, two testing assemblies were used throughout the testing program. The assembly shown in Figure 4 was used so that the tension produced in the bolt could be measured and compared to the gap of the direct tension indicator. The assembly shown in Figure 5 was used to develop a turn-of-nut method. During the testing of the specimens, strain readings, gaps, turns of the nut, and the torques were recorded for each test. Readings were taken every 60 degrees for the 1/2 in. diameter bolts and 30 degrees for the 5/8 in. diameter bolts from the finger tight position. Figures 6 through 19 show a graphical representation of these results.

By using the assembly shown in Figure 4, a relationship of bolt tension versus gap closure was obtained from the first series of tests.

The results are shown in Figures 6 and 7 for 1/2 and 5/8 in. diameter bolts, respectively. It can be seen that for both cases when the gap is closed to the specified gap closure of 0.015 in. the bolt tension exceeds the minimum specified values of 12 kips for the 1/2 in. bolts and 19 kips for the 5/8 in. bolts as specified by the RCRBSJ. Also, as shown in Figure 7, the test data are in good agreement with Ed Estes'[15] load gap curve, which was derived from a particular heat of Coronet Load Indicators for 5/8"ϕA325 bolts. Therefore, it is concluded that the method used in these tests produces favorable results.

In the second series of tests, the testing assembly shown in Figure 5 was used. By using the recorded gaps measured from these tests, the corresponding values of bolt tension were obtained from Figures 6 and 7. The relationship of bolt tension versus nut rotation is shown in Figure 8 for the 1/2 in. diameter A325 bolts and in Figures 9, 10, and 11 for the 5/8 in. diameter A325 bolts with specimens of different grip lengths. For the 1/2 in. diameter A325 bolts, the specified minimum pretension was reached at a nut rotation of 240 degrees. For the 5/8 in. diameter A325 bolts, a rotation of approximately 270 degrees produces the specified minimum pretension. The change of grip lengths of the 5/8 in. diameter bolt assemblies seems to have no effect on the amount of nut rotation required for the specified minimum bolt tension. The results are summarized in Table 8.

As stated earlier, one of the objectives of this study was to determine the pretension produced in a bolt by using the Cornell torques given in Table 2. Figures 12, 13, 14, and 15 are plots of bolt tension versus torque. In all cases it can be seen that the

Cornell torques usually provide sufficient values of pretension as compared with those specified by RCRBSJ. Table 9 summarizes the measured and specified values of bolt tension.

The final relationship obtained from the tests was torque vs. nut rotation. The results are shown in Figures 16, 17, 18, and 19.

4. Summary

To develop a turn-of-nut method for bolted connections composed of cold-formed steel and to determine the bolt tension developed from the torque values used in the original Cornell study, a total of 25 pretension tests were conducted. Ten tests were run on 1/2 in. diameter A325 bolts, and 15 on 5/8 in. A325 bolts.

It was found that from a finger-tight position the minimum specified pretension can be reached by a nut rotation of 240 degrees for the 1/2 in. diameter bolts and of 270 degrees for the 5/8 in. diameter bolts. The change of grip lengths of the connections was found to have little effect on the nut rotation required to reach the minimum specified pretension. Also it was found that the torque values used in the original Cornell study provide sufficient values of pretension as compared with those specified by RCRBSJ as shown in Table 9.

II. BOLTED CONNECTIONS

A. Introduction

The First Progress Report on Bolted Connections in Cold-Formed Steel, which was submitted to the American Iron and Steel Institute in June 1976, outlined several recommendations on the areas of future study. Those recommendations were based on the analysis of the available test data on bolted connections.

The major study on bolted connections in cold-formed steel was carried out at Cornell University in the 1950's. The early program consisted of testing specimens composed of materials with thicknesses equal to or greater than 0.036 inches. In each test, a washer was placed under the head and another under the nut of the bolt, and the bolt was torqued to a specified value established at Cornell. Both symmetric (double shear) and unsymmetric (single shear) connection types were tested. It was found that there are four distinct types of failure modes in bolted connections composed of cold-formed steel depending on the parameters of the connections. They are:

Type 1. Longitudinal shearing of the steel sheets along two practically parallel planes whose distance of separation equals the bolt diameter.

Type 2. Shearing-tearing along two distinctly inclined planes accompanied by a considerable "piling-up" at the material front of the bolt, or bearing failure.

Type 3. Transverse tension-tearing across the sheet.

Type 4. Shearing of the bolt.

It was not until recently that bolted connections without washers were studied by Chong and Matlock[9] and the effects of varying torques on bearing strength by Haussler and Pabers.[11] However, these tests were limited to the study of unsymmetric connections only.

In the summer of 1976, a study was performed to provide additional information as to the effects of torques and washers on the bearing and shear strength of both symmetric and unsymmetric bolted connections composed mainly of materials with thicknesses less than 0.036 inches. This report summarizes the results of 50 tests carried out since the completion of the First Progress Report.

B. Experimental Investigation

1. Design of Test Specimens

To study the effects of torques and washers on the bearing and shear strength of bolted connections, the following parameters were used:

Amount of Torque

Torque = 0

Torque = Cornell Torque (values listed in Tables 1 and 2)

Thickness = 0.024 and 0.047 in.

e/d = 1.5, 2.5, 3.5, and 4.5

With and without washers

Single and double shear connections

All test specimens consisted of blanks with general dimensions as shown in Figure 20. The dimensions were chosen to ensure that the test specimens would fail in bearing or shear of steel sheets. This was accomplished by choosing the dimensions so that the tensile strength of the connection and the shear strength of the bolt were 25% greater than the bearing strength of the connection.

Two types of connections, single and double shear, were tested. Figures 21 and 22 show the configuration of the connected parts for the single and double shear connections, respectively. Table 10 lists the dimensions and the results of bolted connection tests.

ASTM A307 bolts were used for diameters of 1/4 and 3/8 inches. High strength A325 bolts were used for diameters of 3/8 and 1/2 inches. The hole diameters were drilled 1/32 in. larger than the nominal size of the 1/4 and 3/8 in. bolts and 1/16 in. larger than the 1/2 in. bolts.

2. Testing of Specimens

Because some of the test specimens had widths that were too wide to be gripped in the testing machine available in the laboratory, a specially designed supporting unit was connected to each end of the test specimens to transmit the applied load. Figure 23 shows the dimensions of this supporting unit. Plate A, the grip plate, was designed to connect the test specimens, and plate B, the bearing plate, was connected to the crosshead of the testing machine by using four anchor bolts.

The test specimens were connected with both A307 and high-strength A325 bolts with diameters of 1/4, 3/8, and 1/2 inches. Throughout the testing program, the bolts were tightened with a torque wrench. The torque values exerted on the nuts are listed in Table 10. For connections indicated for zero torque, the bolts were first tightened to 100% of the torque values used in the Cornell tests and then released to zero in order to flatten the steel sheets and the burrs at the edge of the holes.

A total of 50 tests were made in a 200,000 pound, universal testing machine, 35 of which were single shear and 15 double shear connections.

To investigate the effect of the washers on the bearing strength of the bolted connections, 34 of the 50 tests were conducted without washers under the bolt head and nut.

3. Test Results and Evaluation of Test Data

As stated in the previous section, it was the purpose of this investigation to study the effects of washers and torque on the shear and bearing strength of bolted connections composed of materials with thicknesses less than 0.036 inches. The test results and several parameters of the 50 bolted connections are listed in Table 10.

Three types of failure modes were observed in the investigation. They are the shearing failure of the connected plates (Type I), bearing failure between the bolt and the sheets (Type II), and a type of failure not defined by the AISI specification, that was due to excessive bolt rotation and warping of the sheets.

a. Shear Strength Study

Of the 50 specimens tested, 12 single shear connections failed as a result of the shearing of the steel sheets, of which eight were connected with washers and four without. The results are shown graphically in Figures 24 and 25. For both cases of with and without washers, it was found that the results can be predicted by the following equation:

$$\sigma_b/F_u = e/d. \qquad (1)$$

In Eq. (1), σ_b is the ultimate bearing stress, F_u the specified minimum ultimate tensile strength of the steel, e the edge distance, and d the diameter of the bolt.

It should be noted that Eq. (1) is the same equation used by the Research Council to determine the allowable bearing stress.

Equation (1) is valid only when e/d does not exceed 3.0 when washers are used and 2.2 when washers are not used. Within these ranges, the structural strength of the bolted connections is governed by a longitudinal shearing type of failure.

Table 12 shows an additional study as to the effects of washers on the shear capacity of single shear connections. Columns 1 and 2 list the specimen numbers and the tested bearing stresses for four single shear specimens that were tested with washers. A reduction factor was determined as shown in Col. 6 by dividing Col. 4 by Col. 2. It can be seen from the reduction factor that the shear capacity of a bolted connection is not significantly affected by the use of washers.

b. Bearing Strength Study

To provide additional information as to the effects of washers on the bearing strength of bolted connections composed of materials with thicknesses less than 0.036 in., both single and double shear specimens were tested. The first series of tests consisted of single shear connections with and without washers. The results and dimensions of the test specimens are given in Table 10. Figure 24 shows a graphical representation of the results of the single shear connections with washers. From these results, the bearing stress can be predicted by using the following formula:

$$\sigma_b/F_u = 3.0. \tag{2}$$

The terms σ_b and F_u were defined earlier. Figure 24 shows that the UMR test results correlate well with the test results of Haussler and Pabers[11] that are given in Table 13.

The results of the single shear connections without washers are shown in Figure 25. From this figure, it can be seen that for specimens for which steel sheets thinner than 0.036 in. were used, the tested bearing values are in the neighborhood of $1.5F_u$, which represents a considerable reduction as compared with $2.2F_u$. This is due to the fact that for this type of connection the failure mode is not the same as the bearing failure used in the AISI Specification. Instead of a bearing failure as expected, the actual failure was due to excessive rotation of the bolt, which caused a premature failure. In addition to the bolt rotation, the steel sheets warped considerably. This type of failure is illustrated in Figure 26.

Four tests were conducted on single shear specimens without washers that were composed of materials with a thickness larger than 0.036 in. It was found that when thicker material is used the bolt is prevented from excessive rotation, thus the bearing strength is increased as shown in Figure 27.

Table 14 shows that the actual reduction in the bearing stress that results from the elimination of washers for single shear connections is approximately 40% for specimens composed of material with a thickness less than 0.036 in.

In addition to the single shear tests, double shear connections without washers were studied. The results are shown in Figures 28 and 29 for connections with thicknesses less than and greater than 0.036 in., respectively. It can be seen that the bearing stress is not significantly affected by the thickness of the material and can be reasonably predicted by:

$$\sigma_b/F_u = 2.2. \tag{3}$$

A study was made to investigate the effect of torque on the bearing strength of single shear connections without washers. Table 15 lists the test specimens that were tightened to the full torque values used in the original Cornell study. For specimens with the same dimensional and mechanical properties, the bearing values were averaged as shown in Col. 4 of Table 15. These values were then used to determine a reduction factor resulting from torque. Table 16 lists the specimens that have the same dimensional and mechanical properties as those in Table 15 except that when these specimens were tested the torque values were varied. The reduction factor given in Col. 5 of Table 16 was determined by dividing the bearing stress values given in Col. 4 by the average values in Table 15. By studying these reduction factors, it can be seen that the effect of torque has little effect on the actual bearing strength of single shear connections without washers.

4. Summary

The purpose of this investigation was to provide additional information of the effects of torque and washers on the shear and bearing capacity of both single and double shear connections composed mainly of materials with a thickness less than 0.036 in. Fifty connection specimens were tested and analyzed.

It was found that the shear capacity of a bolted connection is not affected by the use of washers and that the ultimate bearing stress can be determined by Eq. (1) with reasonable accuracy. It was noted that Eq. (1) is the same equation presently used by the Research Council.

The results of the single shear test specimens designed for a study of bearing strength of bolted connections indicate that if washers are used the bearing stress can be determined by Eq. (2). If the washers are omitted, the test specimens will fail at a much lower value than that predicted by Eq. (2). This is due to the fact that the bolt rotates excessively while the steel sheets warp out of the plane of the load; this causes premature failure. It is concluded that for single shear connections composed of material with a thickness less than 0.036 in. there is approximately a 40% reduction in the bearing strength of the connection that results from the elimination of washers.

For double shear connections without washers, it is shown that the bearing strength of the connection is approximately the same for specimens composed of materials less than and greater than 0.036 inches.

In studying the effect of torque on bearing strength, it was found that for single shear connections without washers the bearing strength is not significantly affected by the amount of torque used in installation.

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APPENDICES

APPENDIX A

Tables

Table 1. Torques Used in Installation of A307 Bolts[6]

Bolt Dia. in.	Torque ft. lb.
1/4	5
3/8	14
1/2	40
5/8	50
3/4	110
1	250

Table 2. Torques Used in Installation of A325 High Strength Bolts[7]

Bolt Dia. in.	Torque ft. lb.
1/4	11.0
3/8	37.5
1/2	95.0
5/8	190.0
3/4	335.0
1.0	750.0

Table 3. Bolt Tension Specified by the Research Council on Riveted and Bolted Structural Joints[12]

Bolt Dia. in.	Minimum Bolt Tension, kips	
	A325 Bolts	A490 Bolts
1/2	12	15
5/8	19	24
3/4	28	35
7/8	39	49
1.0	51	64
1 1/8	56	80
1 1/4	71	102
1 3/8	85	121
1 1/2	103	148

Table 4. Dimensions of Load Cells

Diameter of Bolts (inch)	d_1 (in.)	d_2 (in.)	h (in.)	A ($in.^2$)	r (in.)	h/r
1/2	9/16	1 1/8	1.5	0.746	0.314	4.78
5/8	11/16	1 5/16	1.5	0.982	0.370	4.05

Table 5. Load Indicator Gaps to Give Required Minimum Bolt Tension[14]

Bolt Grade	A325	A490
Under Bolt Head		
Black Finish Bolts	0.015 in.	0.015 in.
All Platings Except Galvanized	0.015 in.	-
Glavanized Bolts	0.010 in.	-
Under Nut with Hardened Washer	0.010 in.	0.010 in.

Table 6. Properties of 1/2 in. Diameter, A325 Bolts Tests

Test No.	Bolt Length (in.)	Grip Length (in.)	Assembly Type
1	3.0	1.980	Fig. 4
2	3.0	1.970	fig. 4
3	3.0	1.980	Fig. 4
4	3.0	2.010	Fig. 4
5	3.0	2.010	Fig. 4
6	1.5	0.309	Fig. 5
7	1.5	0.310	Fig. 5
8	1.5	0.310	Fig. 5
9	1.5	0.313	Fig. 5
10	1.5	0.309	Fig. 5

Table 7. Properties of 5/8 in. Diameter, A325 Bolts Tests

Test No.	Bolt Length (in.)	Grip Length (in.)	Assembly Type
1	3.0	2.174	Fig. 4
2	3.0	2.030	Fig. 4
3	3.0	2.160	Fig. 4
4	3.0	2.170	Fig. 4
5	1.5	0.414	Fig. 5
6	1.5	0.414	Fig. 5
7	1.5	0.410	Fig. 5
8	1.5	0.410	Fig. 5
9	1.5	0.416	Fig. 5
10	1.5	0.773	Fig. 5
11	1.5	0.775	Fig. 5
12	1.5	9.775	Fig. 5
13	1.5	0.358	Fig. 5
14	1.5	0.358	Fig. 5
15	1.5	0.358	Fig. 5

Table 8. Nut Rotations From Finger Tight Condition

Bolt Diameter (in.)	Bolt Length (in.)	Nut Rotation Required to Reach Minimum Specified Protension
1/2	1.5	240 degrees
5/8	1.5	270 degrees

Table 9. Comparison of Cornell Torque Values With the Protension Specified by the RCRBSJ

Bolt Diameter (in.)	Grip Length (in.)	Cornell Torque (ft-lbs)	Bolt Tension (Kips)	
			RCRBSJ	UMR Tests
1/2	0.310	95.0	12.0	14.75
5/8	0.410	190.0	19.0	19.75
5/8	0.775	190.0	19.0	17.75
5/8	0.360	190.0	19.0	18.75

Table 10. Dimensions and Results of Bolted Connection Tests

Test No.	Spec. No.	d (in.)	Torque (ft-lb)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure** Type
1	B-1-1-1-0-SS	1/4	0	0.0270	0.375	0.990	1.50	9.26	44.06	53.25	1.21	82.96	1.56	79.88	1.04	I
2	B-1-1-2-0-SS	1/4	0	0.0275	0.375	0.990	1.50	9.09	44.06	53.25	1.21	74.91	1.41	79.88	0.94	I
3	B-1-1-3-T-SS	1/4	5	0.0270	0.375	0.990	1.50	9.26	44.06	53.25	1.21	86.81	1.63	79.88	1.09	I
4	B-1-1-4-T-SS	1/4	5	0.0280	0.375	0.990	1.50	8.93	44.06	53.25	1.21	85.00	1.60	79.88	1.06	I
5	B-0-1-1-0-SS	1/4	0	0.0270	0.375	0.990	1.50	9.26	44.06	53.25	1.21	77.00	1.45	79.88	0.96	I
6	B-0-1-2-0-SS	1/4	0	0.0270	0.375	1.000	1.50	9.26	44.06	53.25	1.21	82.96	1.56	79.88	1.04	I
7	B-0-1-3-T-SS	1/4	5	0.0260	0.375	1.000	1.50	9.62	44.06	53.25	1.21	78.92	1.48	79.88	0.99	I
8	B-0-1-4-T-SS	1/4	5	0.0260	0.375	1.000	1.50	9.62	44.06	53.25	1.21	78.92	1.48	79.88	0.68	I
9	B-1-2-1-0-SS	3/8	0	0.0270	0.953	3.160	2.54	13.89	44.06	53.25	1.21	135.30	2.54	135.26	1.00	I
10	B-1-2-2-0-SS	3/8	0	0.0265	0.923	3.190	2.46	14.15	44.06	53.25	1.21	127.30	2.39	131.00	0.97	I
11	B-1-2-3-T-SS	3/8	14	0.0265	0.938	3.170	2.50	14.15	44.06	53.25	1.21	127.10	2.39	133.13	0.95	I
12	B-1-2-4-T-SS	3/8	14	0.0265	0.938	3.170	2.50	14.15	44.06	53.25	1.21	127.30	2.39	133.13	0.96	I
13	B-0-2-1-0-SS	3/8	0	0.0270	0.923	3.170	2.46	13.89	44.06	53.25	1.21	79.70	1.50	117.15	0.68	V
14	B-0-2-2-0-SS	3/8	0	0.0270	0.938	3.170	2.50	13.89	44.06	53.25	1.21	75.16	1.41	117.15	0.64	V
15	B-0-2-3-T-SS	3/8	14	0.0270	0.953	3.170	2.54	13.89	44.06	53.25	1.21	80.50	1.54	117.15	0.69	V
16	B-0-2-4-T-SS	3/8	14	0.0270	0.958	3.160	2.50	13.89	44.06	53.25	1.21	79.21	1.49	117.15	0.68	V
17	B-0-3-1-0-SS	3/8	0	0.0270	1.313	3.170	3.50	13.89	44.06	53.25	1.21	76.84	1.44	117.15	0.66	V
18	B-0-3-2-0-SS	3/8	0	0.0270	1.313	3.160	3.50	13.89	44.06	53.25	1.21	81.48	1.53	117.15	0.70	V
19	B-0-3-3-T-SS	3/8	14	0.0270	1.313	3.170	3.50	13.89	44.06	53.25	1.21	86.12	1.62	117.15	0.74	V
20	B-0-3-4-T-SS	3/8	14	0.0270	1.313	3.170	3.50	13.89	44.06	53.25	1.21	87.01	1.63	117.15	0.74	V
21	B-0-3-7-T-SS	3/8	14	0.0260	1.313	3.220	3.50	14.42	45.03	52.03	1.16	85.44	1.64	114.47	0.75	V
22	B-0-3-8-T-SS	3/8	14	0.0260	1.300	3.230	3.46	14.42	45.03	52.03	1.16	80.62	1.58	114.47	0.70	V
23	B-0-3-9-T-DS	3/8	14	0.0255	1.313	3.219	3.50	14.71	45.03	52.03	1.16	107.20	2.06	114.47	0.94	I+II
24	B-0-3-10-T-DS	3/8	14	0.0255	1.300	3.234	3.46	14.71	45.03	52.03	1.16	107.00	2.06	114.47	0.93	I+II
25	B-0-4-1-0-SS	3/8	0	0.0260	1.688	3.160	4.50	14.42	44.06	53.25	1.21	77.64	1.46	117.15	0.66	V
26	B-0-4-2-0-SS	3/8	0	0.0260	1.703	3.190	4.54	14.42	44.06	53.25	1.21	76.41	1.43	117.15	0.65	V
27	B-0-4-3-T-SS	3/8	14	0.0270	1.688	3.170	4.50	13.89	44.06	53.25	1.21	79.01	1.48	117.15	0.67	V
28	B-0-4-4-7-SS	3/8	14	0.0270	1.688	3.170	4.50	13.89	44.06	53.25	1.21	82.96	1.56	117.15	0.71	V
29	B-0-4-7-T-DS	3/8	14	0.0260	1.673	3.234	4.46	14.42	45.03	52.03	1.16	100.10	1.92	114.47	0.82	I+II
30	B-0-4-8-T-DS	3/8	14	0.0260	1.688	3.234	4.5	14.42	45.03	52.03	1.16	94.15	1.81	114.47	0.82	I+II

Table 10 (cont'd)

Test No.	Spec. No.	d (in.)	Torque (ft-lb)	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{cal}}$	Failure** Type
31	B-0-5-1-T-DS	1/2	95	0.0460	1.720	6.875	3.44	10.87	43.83	55.73	1.27	110.35	1.98	122.61	0.90	II
32	B-0-5-2-T-DS	1/2	95	0.0460	1.720	6.875	3.44	10.87	43.83	55.73	1.27	115.00	2.06	122.61	0.94	II
33	B-0-5-3-T-DS	1/2	95	0.0460	1.750	6.750	3.50	10.87	43.83	55.73	1.27	114.26	2.05	122.61	0.93	II
34	B-0-5-4-T-DS	1/2	95	0.0470	1.750	6.840	3.50	10.64	43.83	55.73	1.27	122.04	2.19	122.61	1.00	II
35	B-0-5-5-T-DS	1/2	95	0.0470	1.750	6.840	3.50	10.64	43.83	55.73	1.27	120.43	2.16	122.61	0.98	II
36	B-0-6-1-T-DS	1/2	95	0.0460	2.250	6.750	4.50	10.87	43.83	55.73	1.27	116.30	2.09	122.61	0.95	II
37	B-0-6-2-T-DS	1/2	95	0.0460	2.250	6.750	4.50	10.87	43.83	55.73	1.27	104.57	1.88	122.61	0.85	II
38	B-0-6-3-T-DS	1/2	95	0.0460	2.250	6.750	4.50	10.87	43.83	55.73	1.27	107.40	1.93	122.61	0.88	II
39	B-0-7-1-T-SS	1/2	95	0.0460	1.750	6.800	3.50	10.87	43.83	55.73	1.27	124.35	2.23	122.61	1.01	II
40	B-0-7-2-T-SS	1/2	95	0.0460	1.750	6.800	3.50	10.87	43.83	55.73	1.27	138.70	2.49	122.61	1.13	II
41	B-0-7-3-T-SS	1/2	95	0.0470	1.750	6.844	3.50	10.64	43.83	55.73	1.27	191.90	3.44	122.61	1.57	II
42	B-0-7-4-T-SS	1/2	95	0.0470	1.750	6.844	3.50	10.64	43.83	55.73	1.27	164.68	2.95	122.61	1.34	II
43	B-1-8-3-T-SS	3/8	37	0.0250	1.313	5.220	3.50	15.00	45.00	52.00	1.16	146.13	2.81	156.00	0.94	II
44	B-1-8-3-T-SS	3/8	37	0.0250	1.313	5.230	3.50	15.00	45.00	52.00	1.16	130.13	2.50	156.00	0.83	II
45	B-1-9-1-T-SS	3/8	37	0.0240	1.658	5.220	4.42	15.63	45.00	52.00	1.16	160.00	3.08	156.00	1.03	II
46	B-1-9-2-T-SS	3/8	37	0.024	1.688	5.220	4.50	15.63	45.00	52.00	1.16	137.56	2.65	156.00	0.88	II
47	B-1-9-3-T-SS	3/8	37	0.024	1.688	5.220	4.50	15.63	45.00	52.00	1.16	190.22	3.66	156.00	1.22	II
48	B-1-10-1-T-DS	1/2	95	0.025	1.750	7.830	3.50	20.00	45.00	52.00	1.16	178.00	3.42	156.00	1.41	II
49	B-1-10-2-T-DS	1/2	95	0.025	1.750	7.830	3.50	20.00	45.00	52.00	1.16	161.44	3.10	156.00	1.03	II
50	B-1-10-3-T-DS	1/2	95	0.025	1.750	7.840	3.50	20.00	45.00	52.00	1.16	170.00	3.27	156.00	1.10	II

* A summary of the calculations used to determine $(\sigma_b)_{cal}$ are given in Table 11.

** The types of failure are defined as follows:

I - Longitudinal shearing of the steel sheets

II - Bearing failure between steel sheet and bolt

V - Failure due to excessive bolt rotation and warping of steel sheets

++ The specimens are designated as:

B-1-1-1-0 —— Type of Torque: 0 - no torque

Test No.

No. of Specimen

Washers used: 0 - No
1 - Yes

Bearing test

Table 11. Summary of Equations Used to Determine $(\sigma_b)_{cal}$ Listed in Table 10

(a) With Washers

e/d	Calculated Bearing Stress for Single and Double Shear Connections $(\sigma_b)_{cal}$ (ksi)
$\leq$ 3.0	$(e/d)F_u$
> 3.0	$3.0F_u$

(b) Without Washers

e/d	Calculated Bearing Stress for Single and Double Shear Connections $(\sigma_b)_{cal}$ (ksi)
$\leq$ 2.2	$(e/d)F_u$
> 2.2	$2.2F_u$

Table 12. Effect of Washers on the Shear Capacity Of Single Shear Conditions, e/d < 2.2

1	2	3	4	5	6	7
With Washers		Without Washers		Torque (ft-lb)	Reduction Factor (col 4/col 2)	Reference
Spec. No.	$(\sigma_b)_{test}$ (ksi)	Spec. No.	$(\sigma_b)_{test}$ (ksi)			
B-1-1-1-0-SS	82.96	B-0-1-1-0-SS	77.00	0	0.928	See Table 10
B-1-1-2-0-SS	74.91	B-0-1-2-0-SS	82.96	0	1.107	do
B-1-1-3-T-SS	86.81	B-0-1-3-T-SS	78.92	5	0.905	do
B-1-1-4-T-SS	85.00	B-0-1-4-T-SS	78.92	5	0.928	do

Table 13. Tests on Single Shear Connections With Various Torques[11]

Test No.	d (in.)	Torque (ft-lb)	t (in.)	e (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y	$(\sigma_b)_{test}$ (ksi)	$\frac{(\sigma_b)_{test}}{F_u}$	Washers Used
1	1/4	0	0.0236	.875	3.5	10.60	62.2	72.6	1.17	142.90	1.97	No
2	1/4	2.5	0.0236	.875	3.5	10.60	62.2	72.6	1.17	144.92	2.00	No
3	1/4	5.0	0.0236	.875	3.5	10.60	62.2	72.6	1.17	143.73	1.98	No
4	1/4	0	0.0236	.875	3.5	10.60	62.2	72.6	1.17	179.83	2.48	Yes
5	1/4	2.5	0.0236	0.875	3.5	10.60	62.2	72.6	1.17	237.63	3.27	Yes
6	1/4	5.0	0.0236	0.875	3.5	10.60	62.2	72.6	1.17	246.27	3.39	Yes
7	3/8	0	0.0256	1.313	3.5	15.90	62.2	72.6	1.17	109.38	1.51	No
8	3/8	7.0	0.0236	1.313	3.5	15.90	62.2	72.6	1.17	105.42	1.45	No
9	3/8	14.0	0.0236	1.313	3.5	15.90	62.2	72.6	1.17	103.28	1.42	No
10	3/8	0	0.0236	1.313	3.5	15.90	62.2	72.6	1.17	162.60	2.24	Yes
11	3/8	7.0	0.0236	1.313	3.5	15.90	62.2	72.6	1.17	203.50	2.80	Yes
12	3/8	14.0	0.0236	1.313	3.5	15.90	62.2	72.6	1.17	185.31	2.55	Yes

Table 14. Effect of Washers on the Bearing Capacity of Single Shear Connections e/d $\geq$ 2.2

1	2	3	4	5	6	7
With Washers		Without Washers				
Spec. No.	$(\sigma_b)_{test}$ (ksi)	Spec. No.	$(\sigma_b)_{test}$ (ksi)	Torque (ft-lb)	Reduction Factor (col 4/col 2)	Reference
B-1-2-1-0-SS	135.30	B-0-2-1-0-SS	79.70	0	0.589	See Table 10
B-1-2-2-0-SS	127.30	B-0-2-2-0-SS	75.16	0	0.590	do
4	179.83	1	142.90	0	0.795	Haussler[11]
10	162.60	7	109.38	0	0.673	Haussler[11]
5	237.63	2	144.92	2.5	0.610	Haussler[11]
6	246.27	3	143.73	5.0	0.584	Haussler[11]
11	203.50	8	105.42	7.0	0.518	Haussler[11]
B-1-2-3-T-SS	127.10	B-0-2-3-T-SS	80.50	14.0	0.633	See Table 10
B-1-2-4-T-SS	127.30	B-0-2-4-T-SS	79.21	14.0	0.622	do
12	185.31	9	103.28	14.0	0.552	Haussler[11]

Table 15. Average Bearing Stress of Single Shear Connections Without Washers. (Using Full Cornell Torque)

1	2	3	4	5
Spec. No.	Torque (ft-lb)	e/d	$(\sigma)_{test-0}$ (ksi)	Reference
B-0-2-3-T-SS	14	2.54	80.50	See Table 10
B-0-2-4-T-SS	14	2.50	79.21	do
		Average	79.86	
B-0-3-3-T-SS	14	3.50	86.12	See Table 10
B-0-3-4-T-SS	14	3.50	87.01	do
B-0-3-7-T-SS	14	3.50	85.44	do
B-0-3-8-T-SS	14	3.46	80.61	do
		Average	84.80	
B-0-4-3-T-SS	14	4.50	79.01	See Table 10
B-0-4-4-T-SS	14	4.50	82.96	do
		Average	80.99	
3	5.0	3.5	143.73	See Table 13
9	14.0	3.5	103.28	do

Table 16. Effect of Torque on the Bearing Strength of Single Shear Connections Without Washers

1	2	3	4	5	6
Spec. No.	Torque (ft-lb)	e/d	$(\sigma_b)_{test}$ (ksi)	Reduction Factor $\frac{(\sigma_b)_{test}}{Ave.(\sigma_b)_{test-0}}$	Reference
B-0-2-1-0-SS	0	2.46	79.70	0.998	See Table 10
B-0-2-2-0-SS	0	2.50	75.16	0.941	do
B-0-3-1-0-SS	0	3.50	76.84	0.906	do
B-0-3-2-0-SS	0	3.50	81.48	0.961	do
B-0-4-1-0-SS	0	4.50	77.64	0.959	do
B-0-4-2-0-SS	0	4.54	76.41	0.943	do
1	0	3.50	142.90	0.994	See Table 13
2	2.5	3.50	144.92	1.008	do
7	0	3.50	109.38	1.059	do
8	7.0	3.50	105.42	0.980	do

* The corresponding average values of $(\sigma_b)_{test}$ for connections using full torque are given in Table 15.

APPENDIX B

Figures

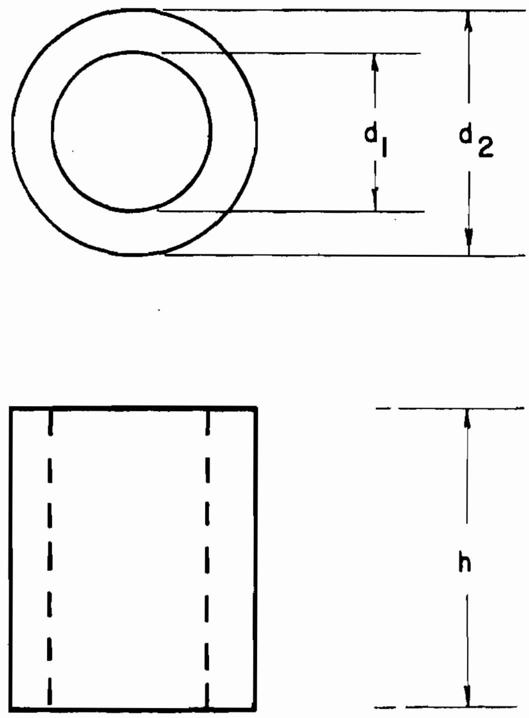

Fig. 1 Load Cell Dimensions

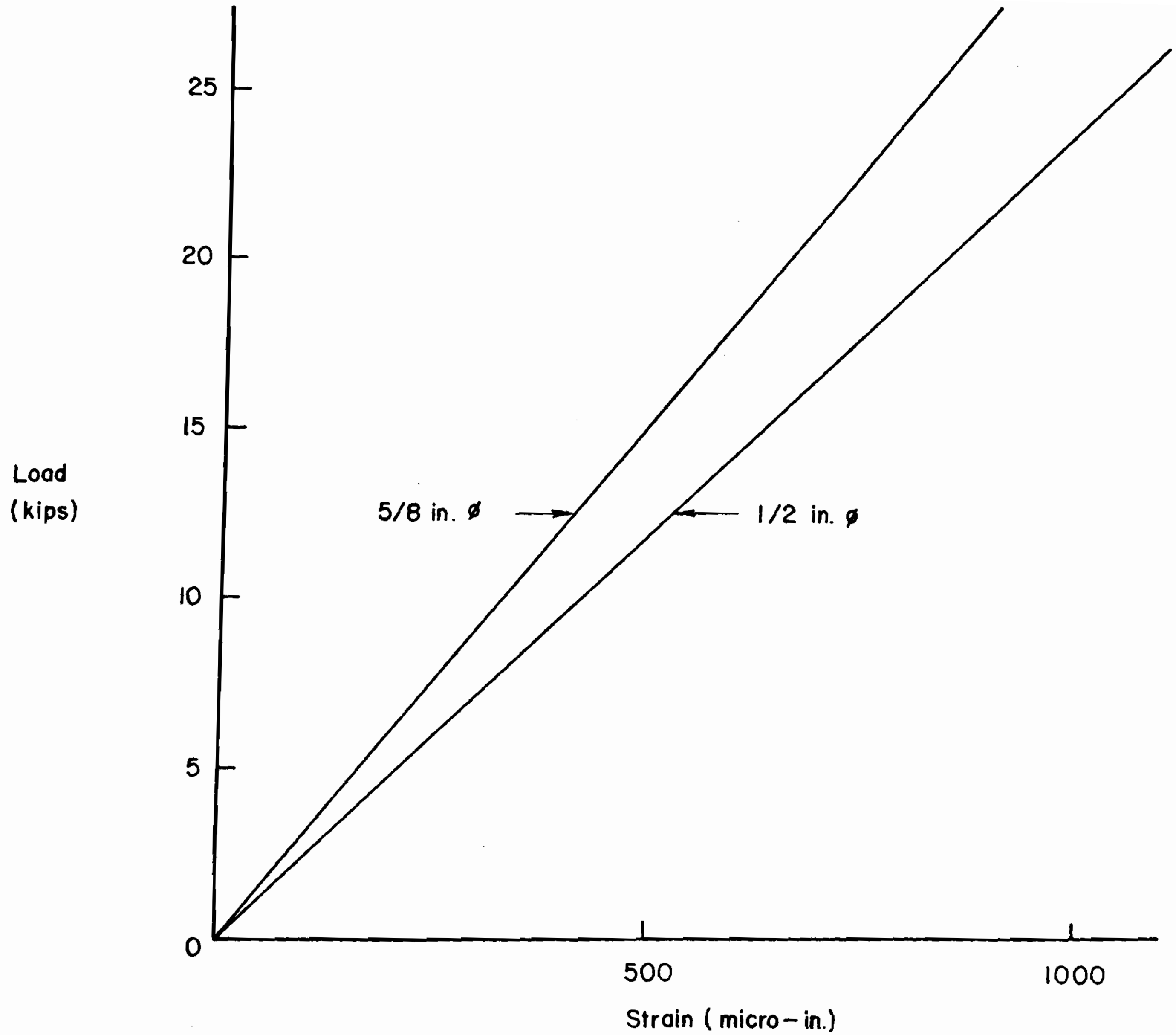

Fig. 2 Load Cyclinder Calibration Curves for 1/2 in. and 5/8 in.ϕA325 Bolts

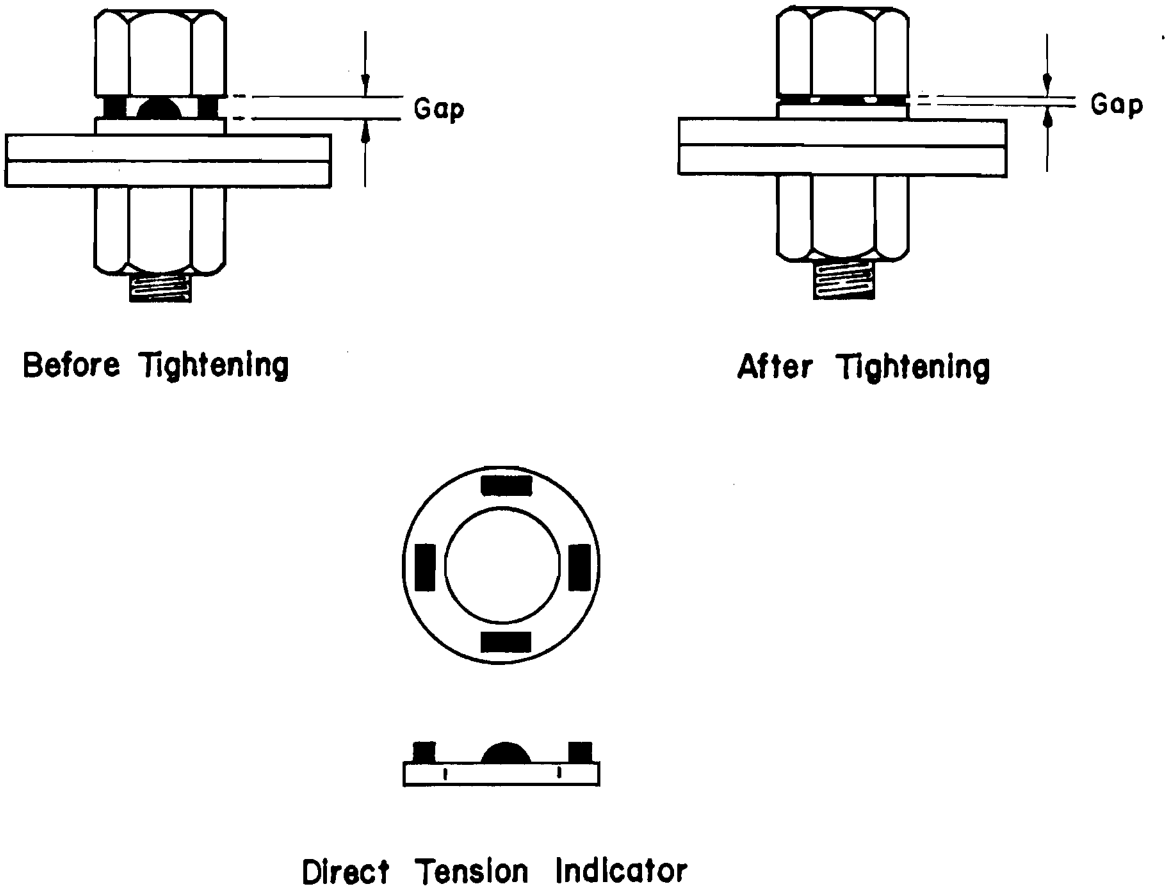

Fig. 3 Direct Tension Indicator

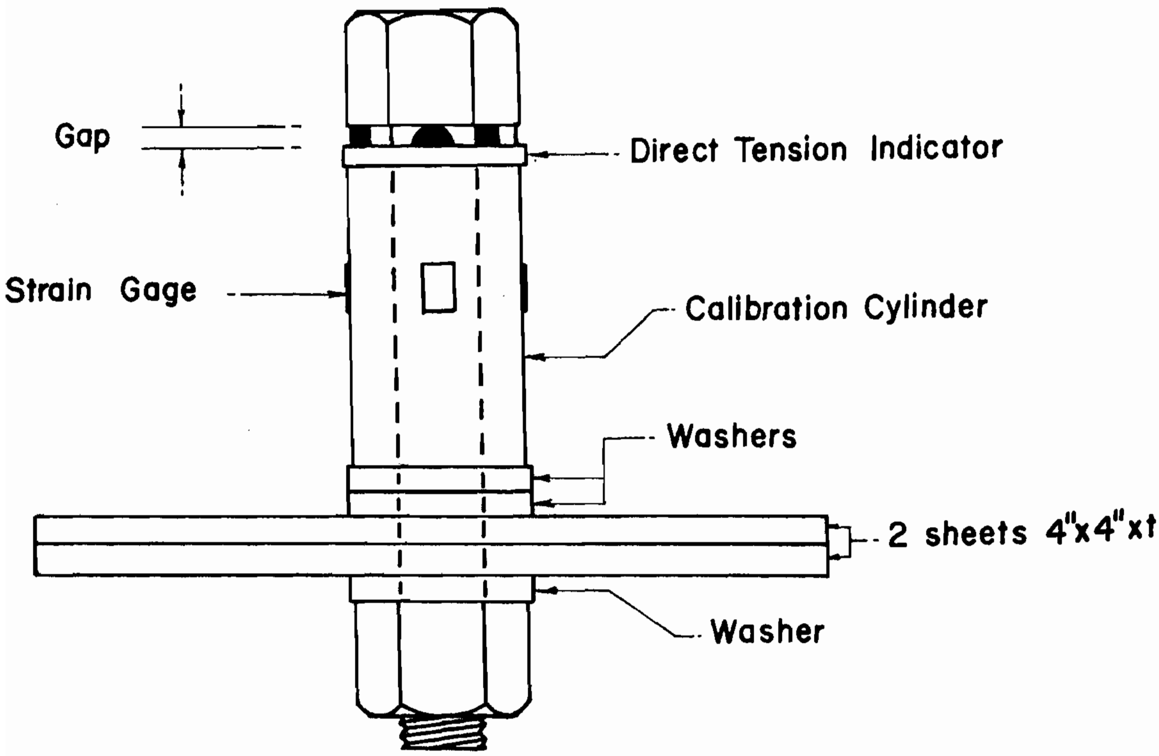

Fig. 4 Pretension Test Assembly Used for
Calibrating Direct Tension Indicator

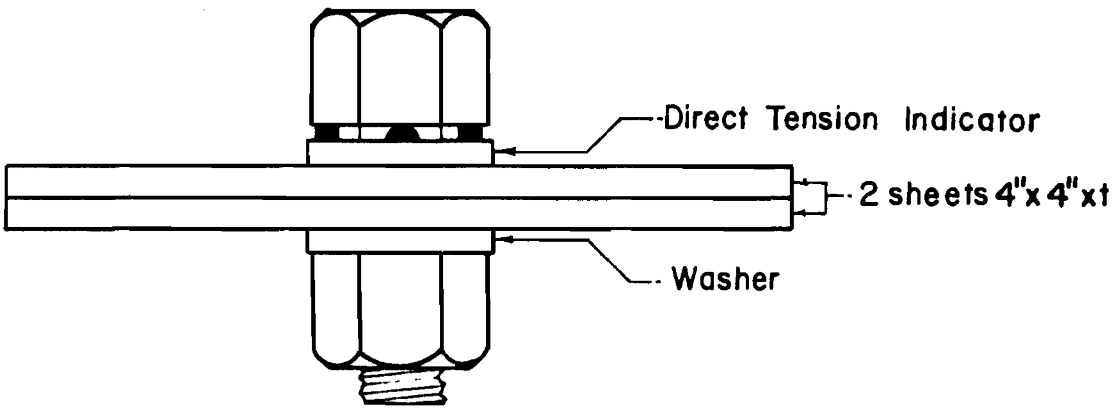

Fig. 5 Pretension Test Assembly

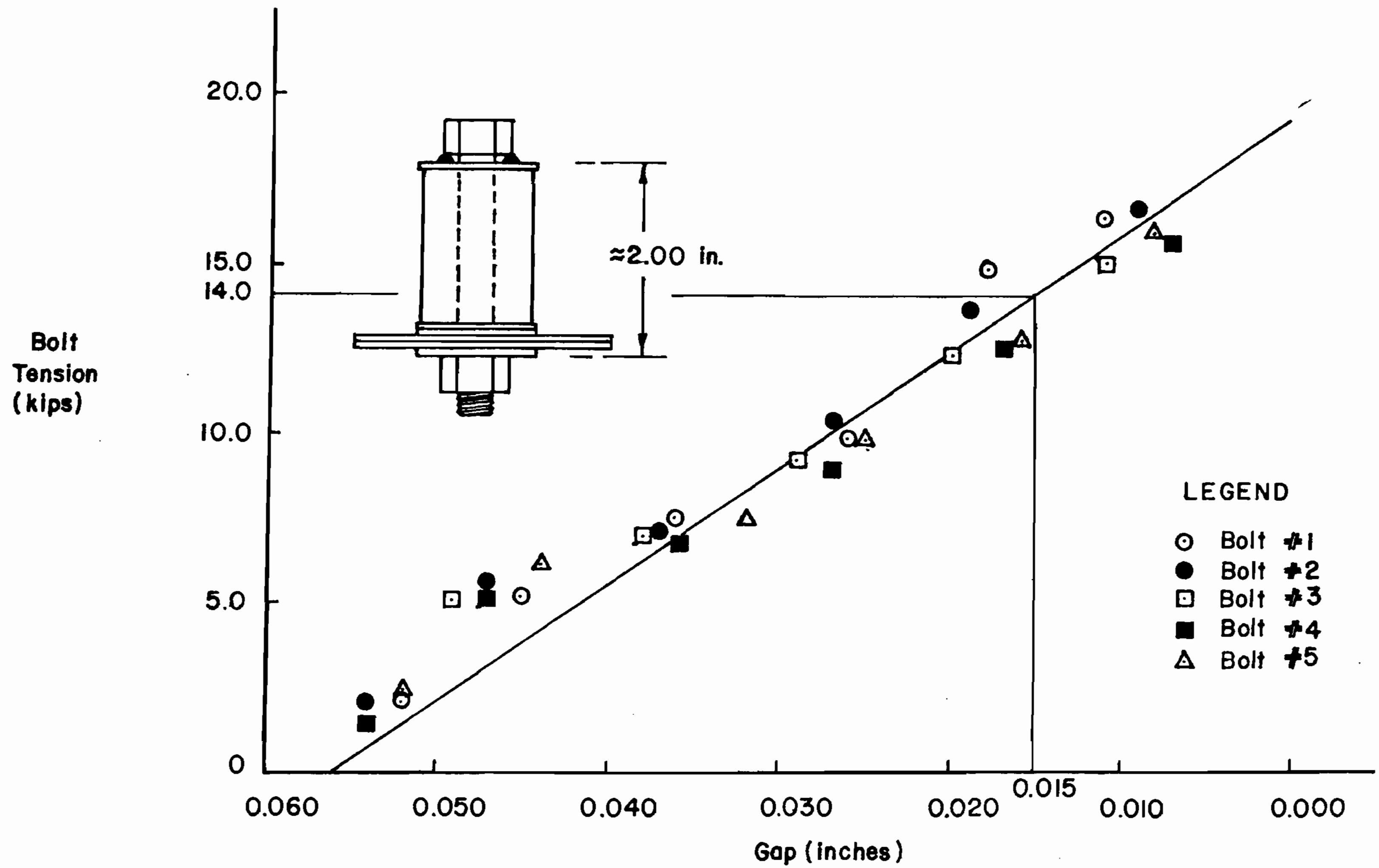

Fig. 6 Calibration of Direct Tension Indicator
Using 1/2 in.ϕA325 Bolts

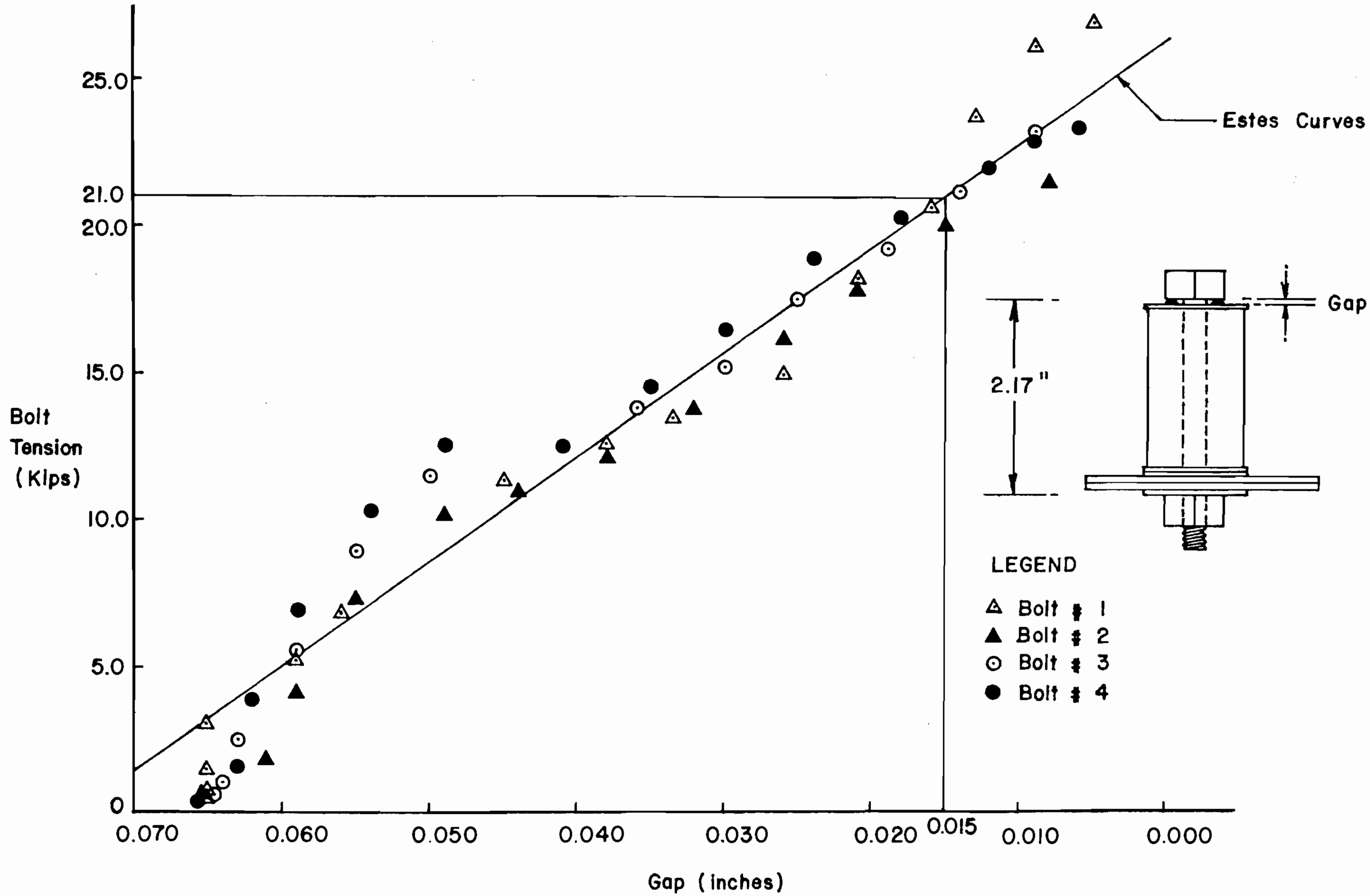

Fig. 7 Calibration of Direct Tension Indicator Using 5/8 in.ϕA325 Bolts

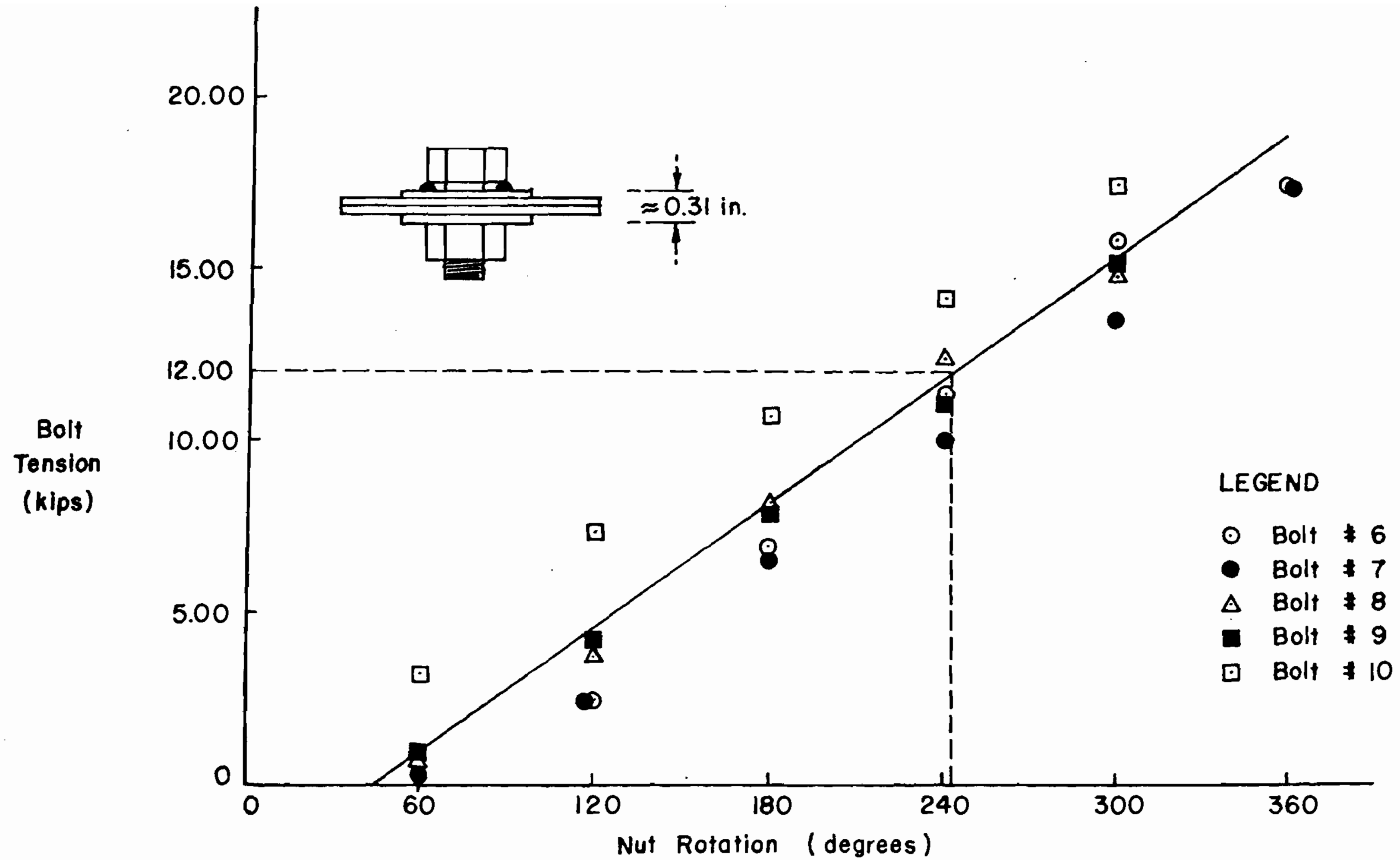

Fig. 8 Relationship of Bolt Tension vs. Nut Rotation for 1/2 in. ϕA325 Bolts

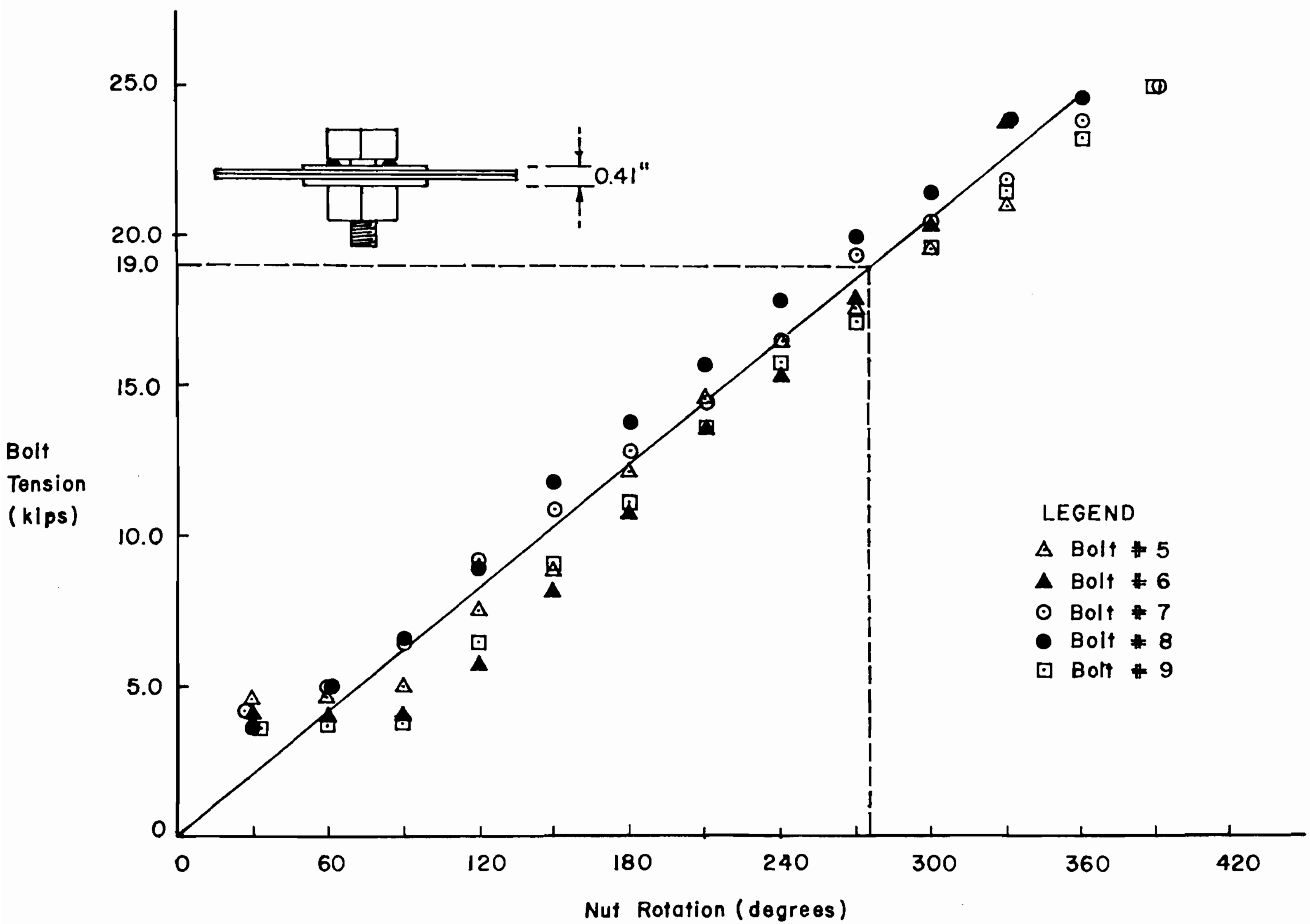

Fig. 9 Relationship of Bolt Tension vs. Nut Rotation for 5/8 in.ϕA325 Bolts

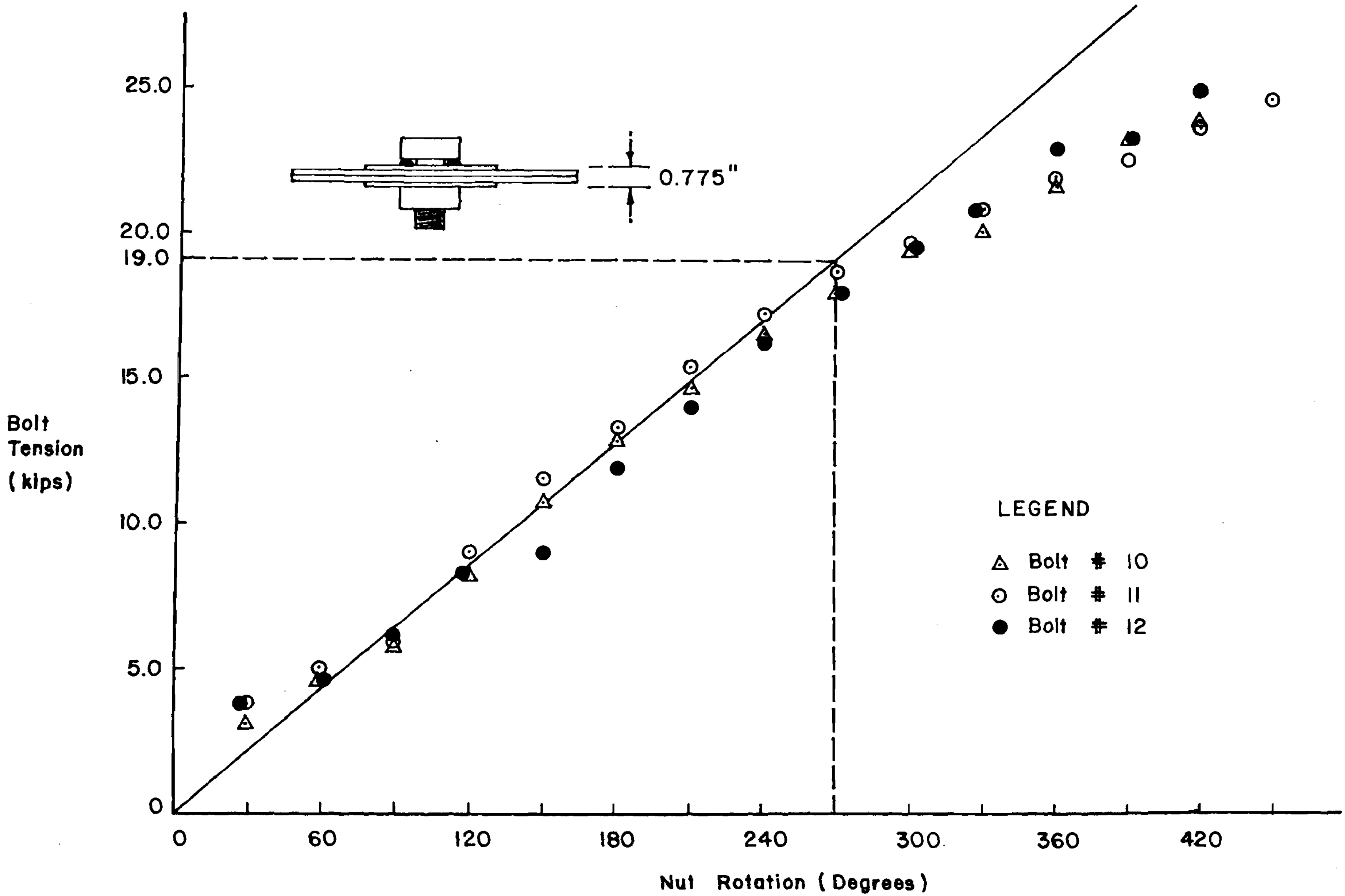

Fig. 10 Relationship of Bolt Tension vs. Nut Rotation for 5/8 in.ϕA325 Bolts

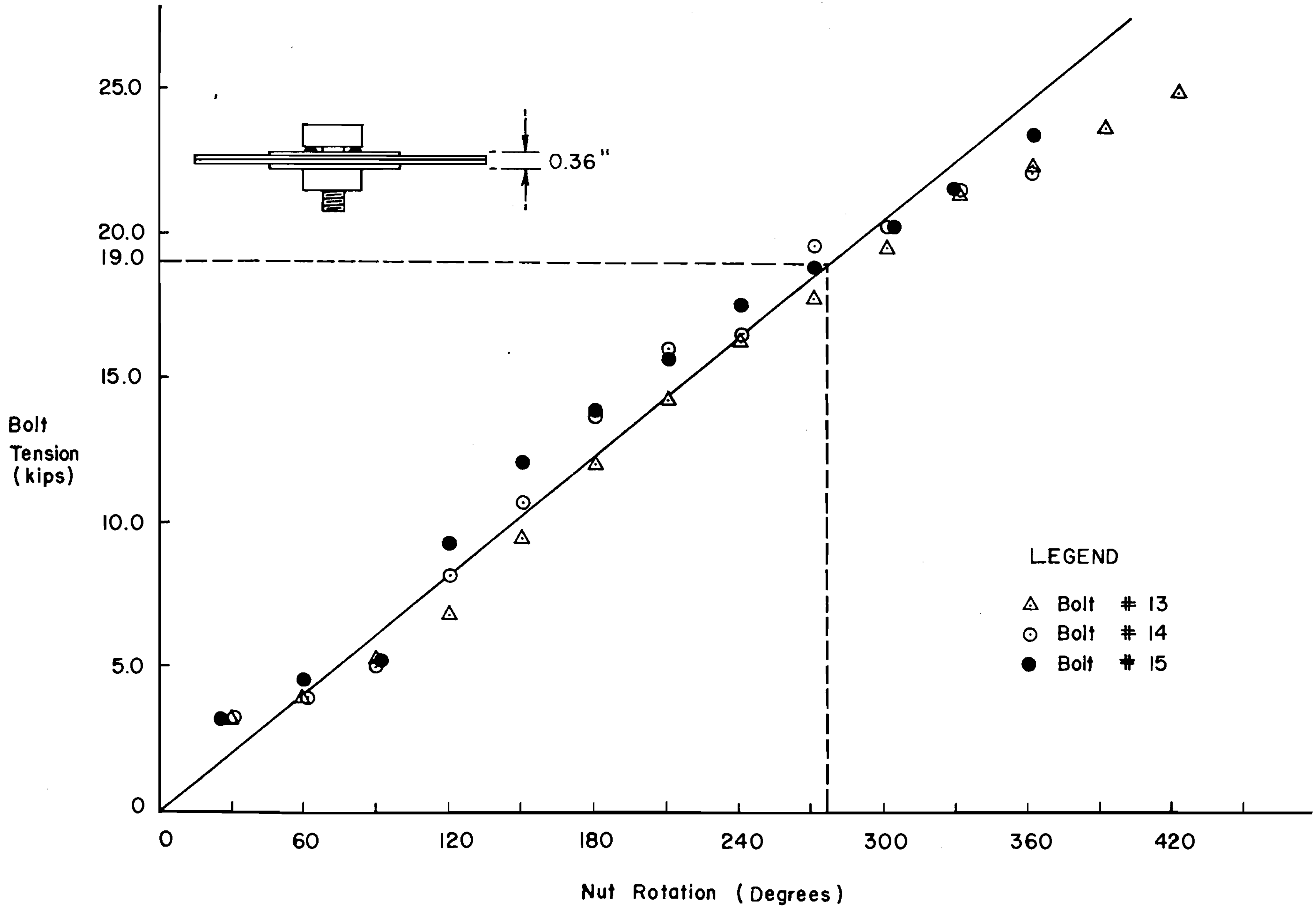

Fig. 11 Relationship of Bolt Tension vs. Nut Rotation for 5/8 in. ϕA325 Bolts

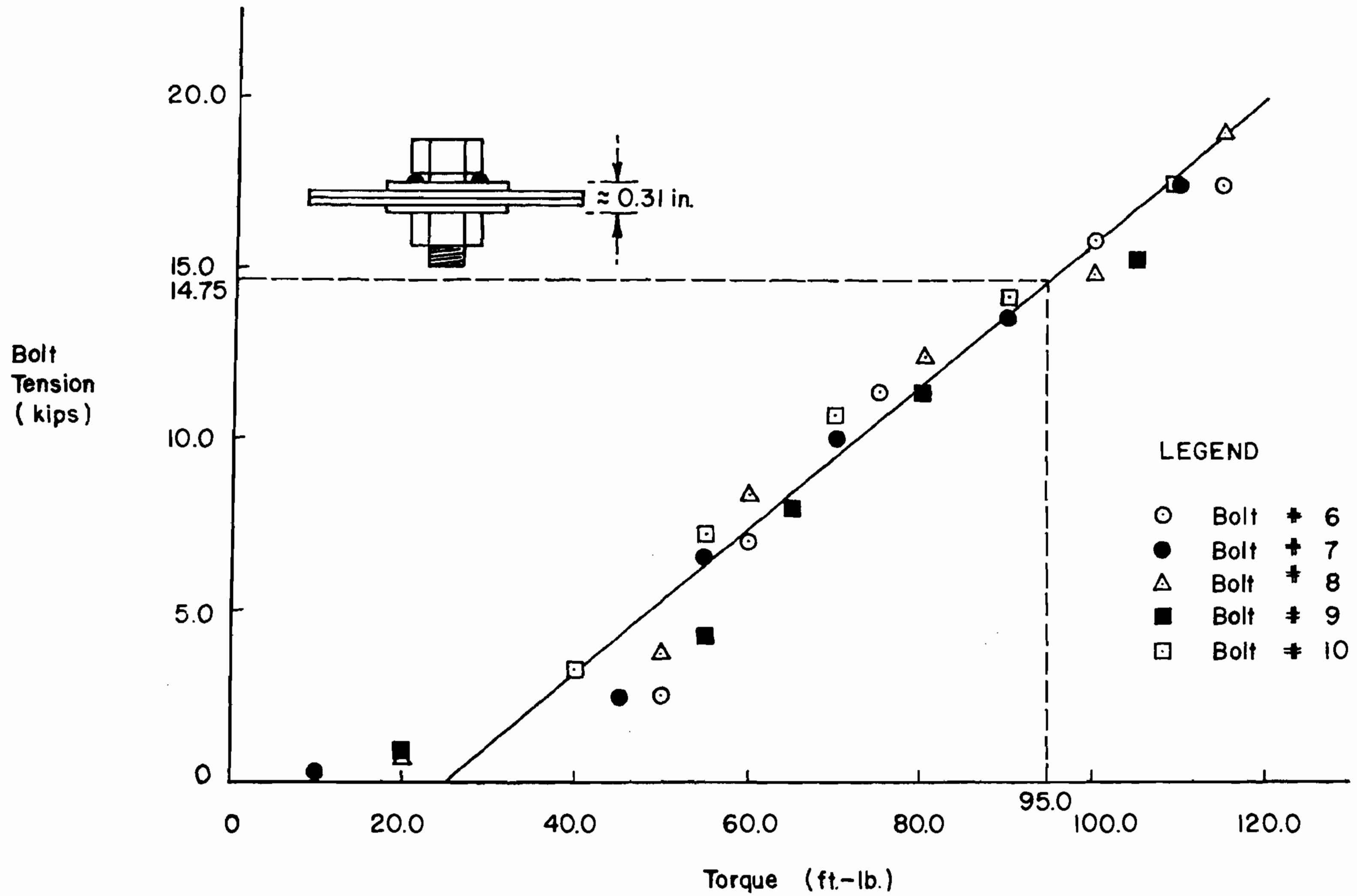

Fig. 12 Relationship of Bolt Tension vs. Torque for 1/2 in. ϕA325 Bolts

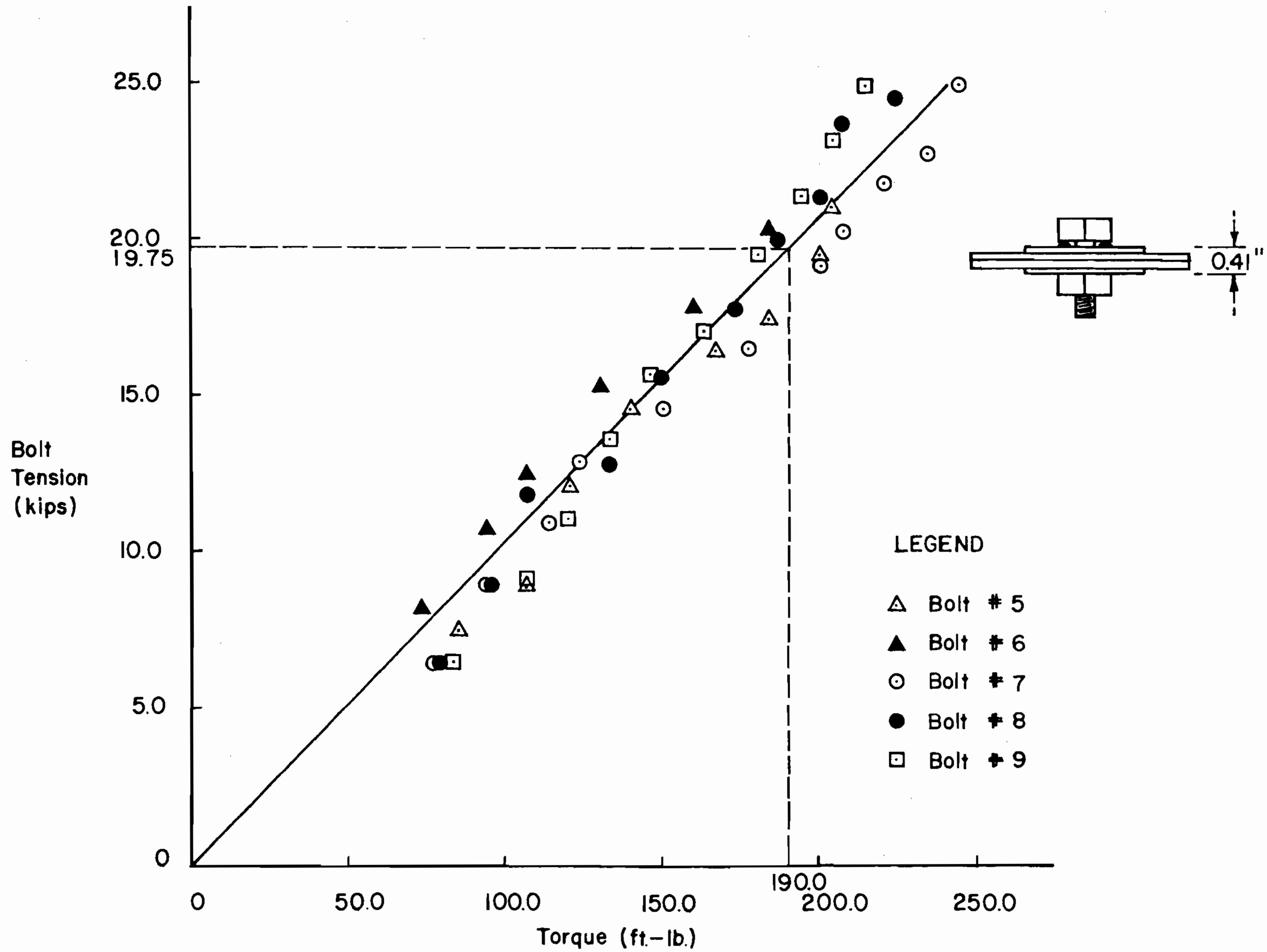

Fig. 13 Relationship of Bolt Tension vs. Torque for 5/8 in. ϕA325 Bolts

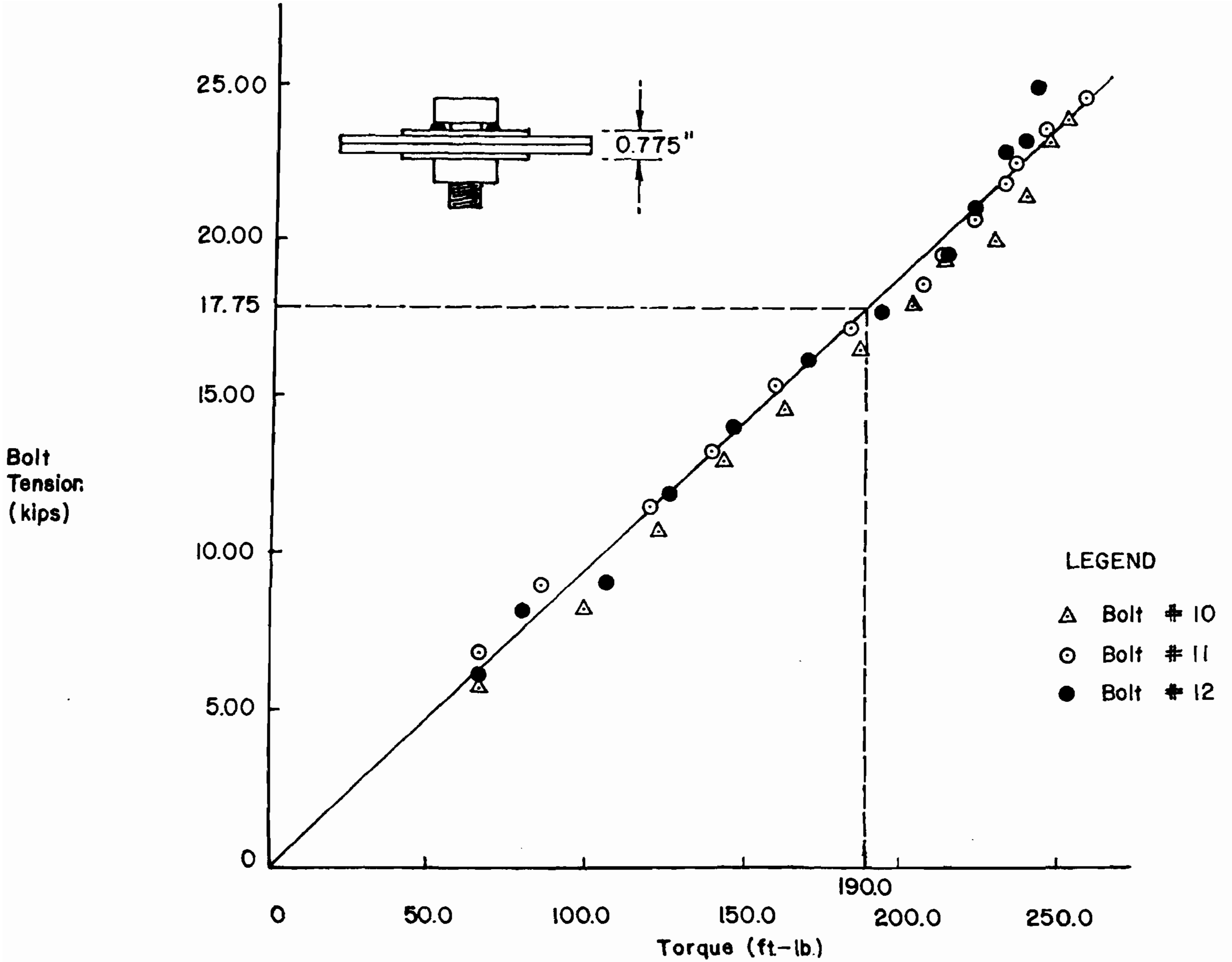

Fig. 14 Relationship of Bolt TEnsion vs. Torque for 5/8 in. ϕA325 Bolts

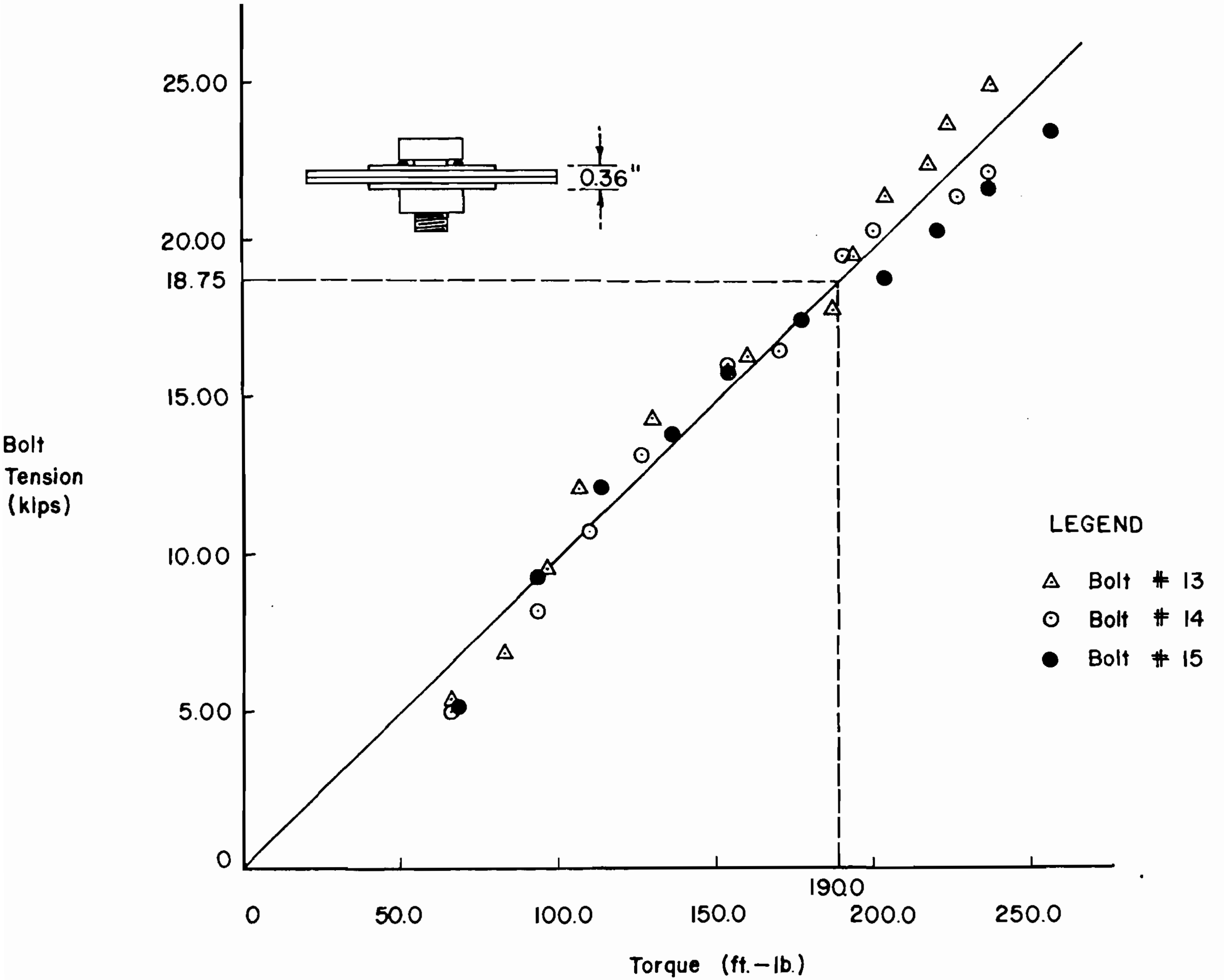

Fig. 15 Relationship of Bolt Tension vs. Torque for 5/8 in. ϕA325 Bolts

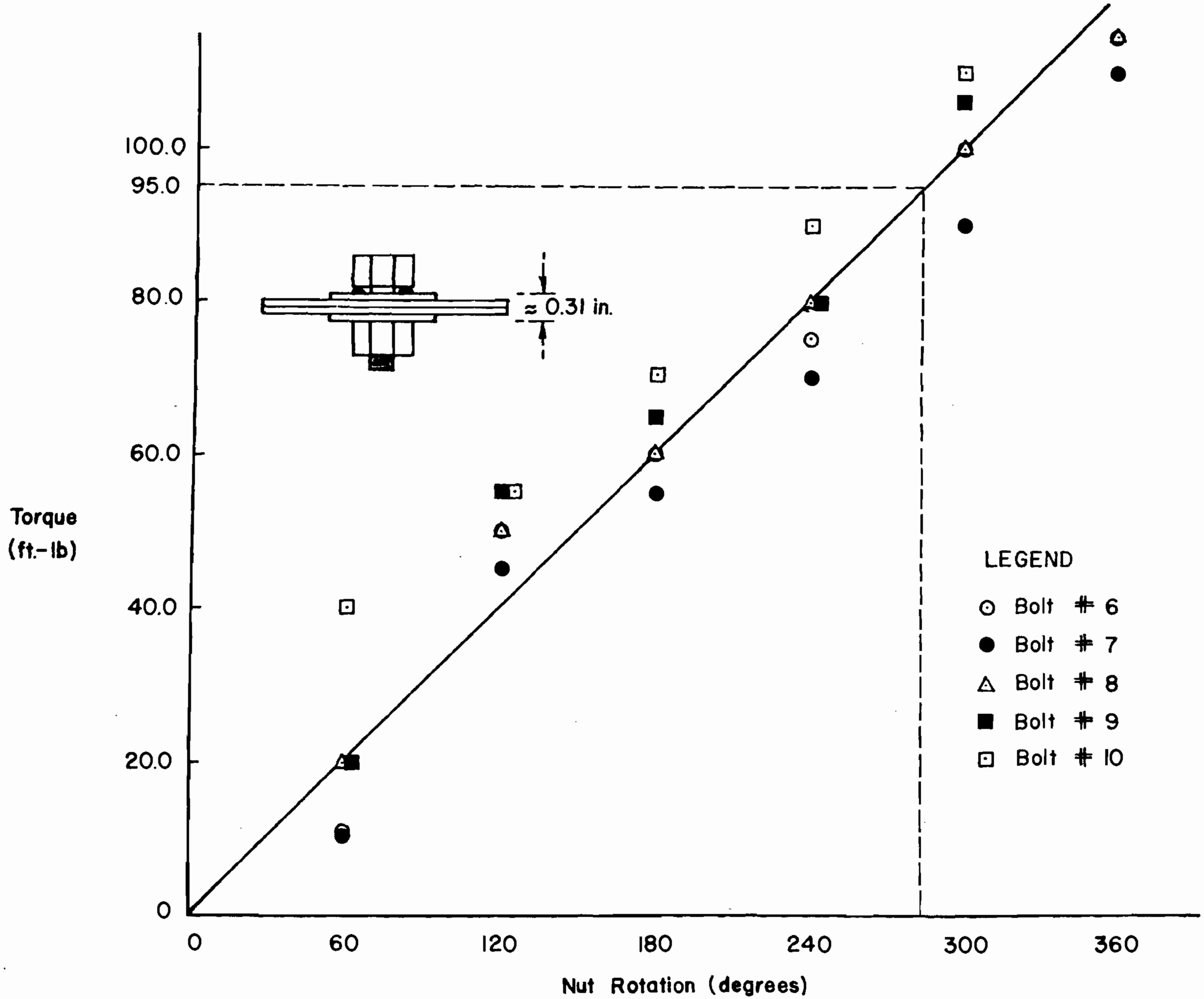

Fig. 16 Relationship of Torque vs. Nut Rotation for 1/2 in. ϕA325 Bolts

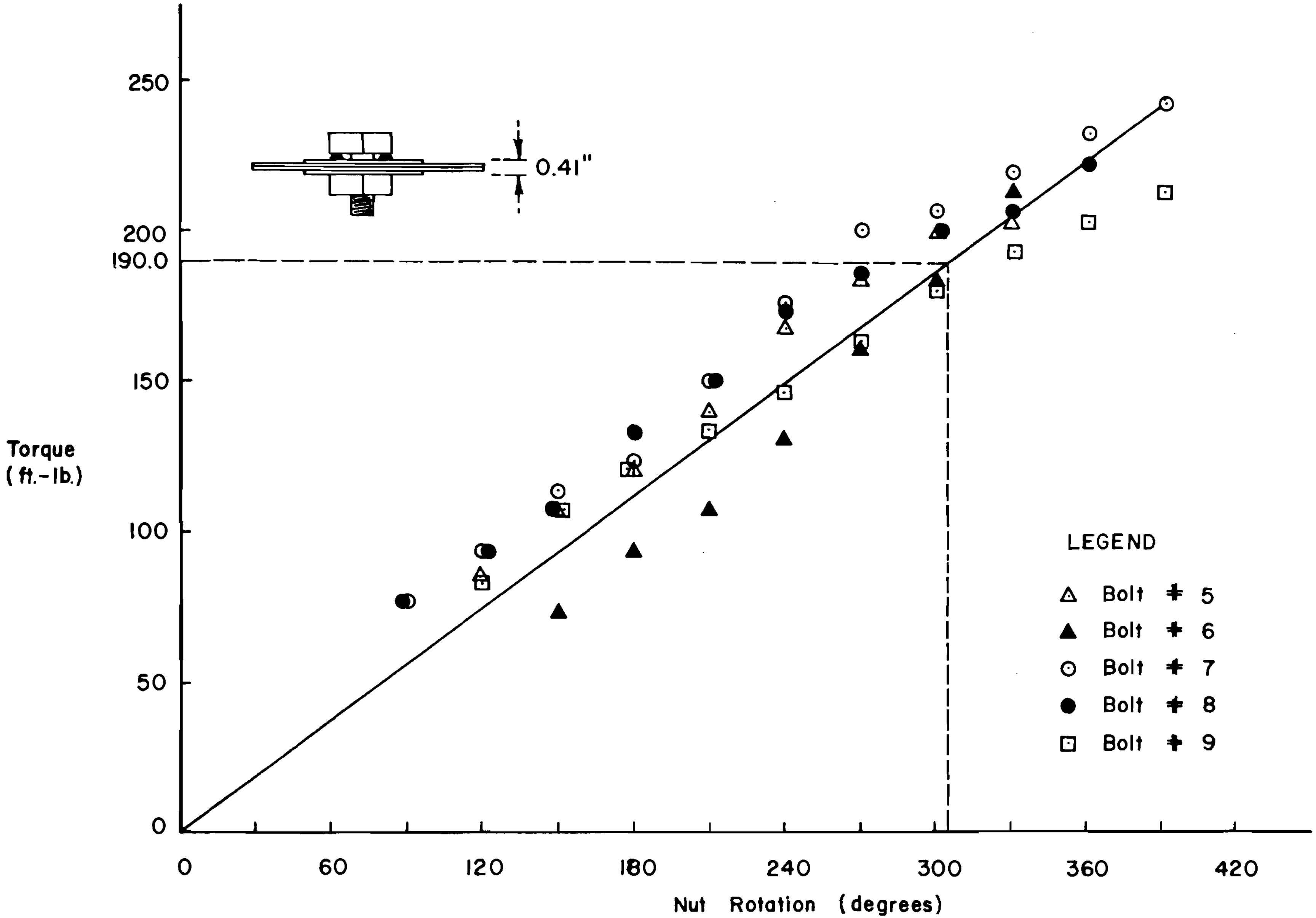

Fig. 17 Relationship of Torque vs. Nut Rotation for 5/8 in. ϕA325 Bolts

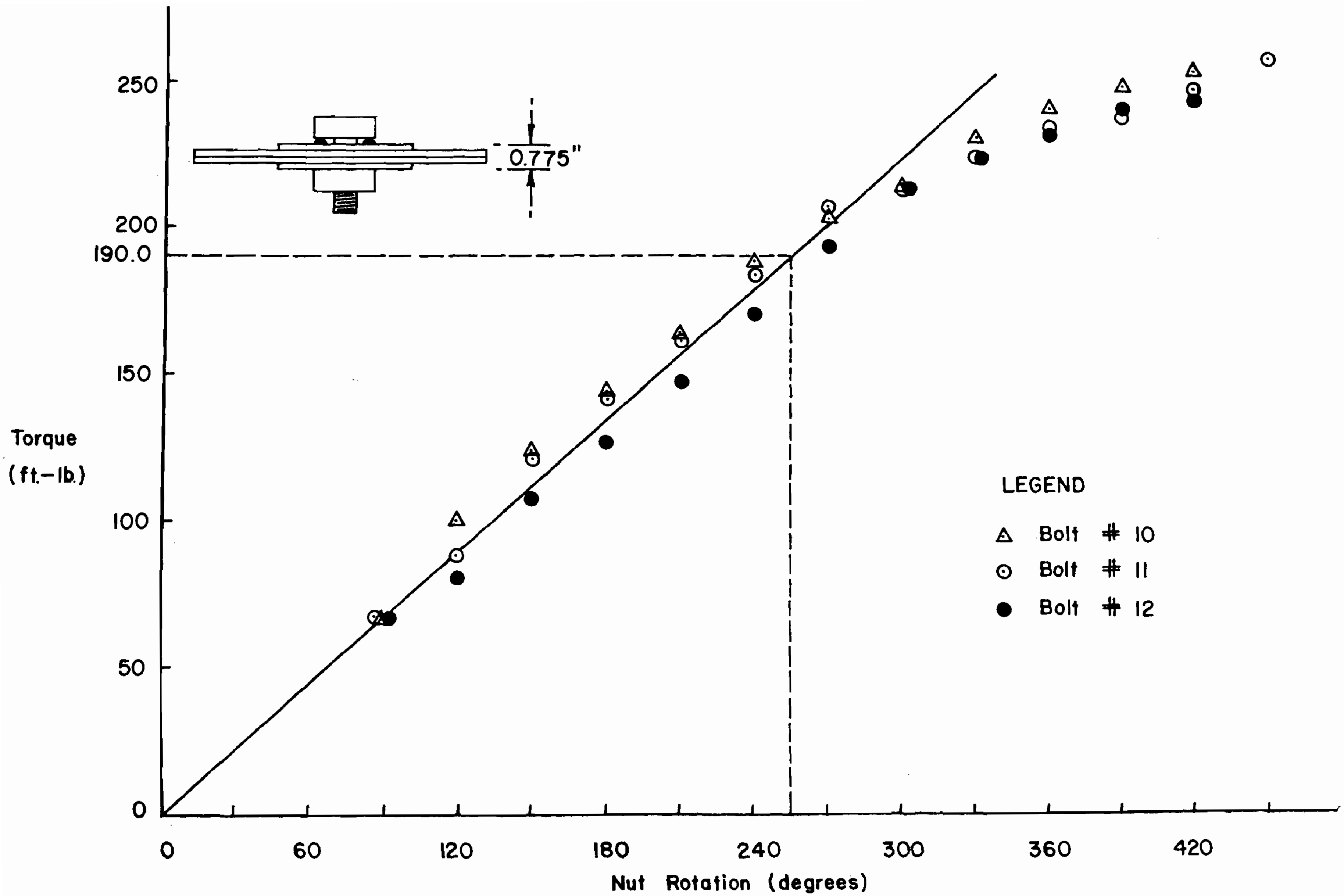

Fig. 18 Relationship of Torque vs. Nut Rotation for 5/8 in. ϕA325 Bolts

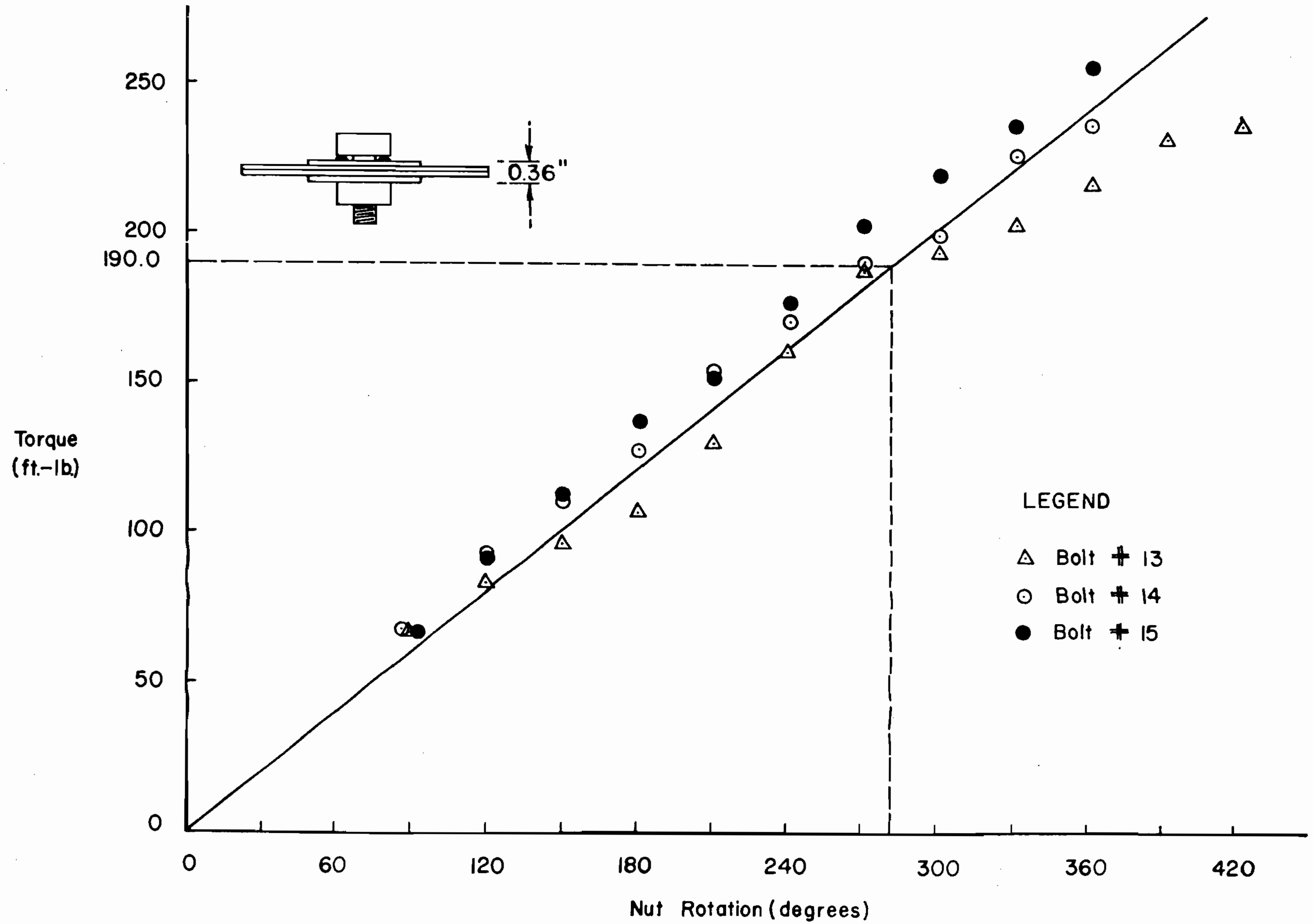

Fig. 19 Relationship of Torque vs. Nut Rotation for 5/8 in. ϕA325 Bolts

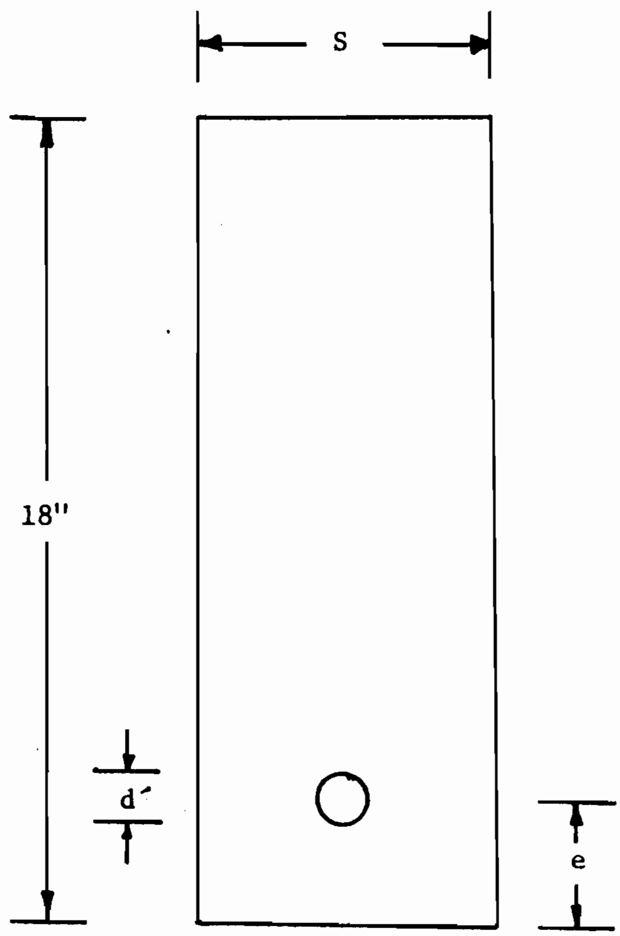

Fig. 20 Test Specimen Blanks

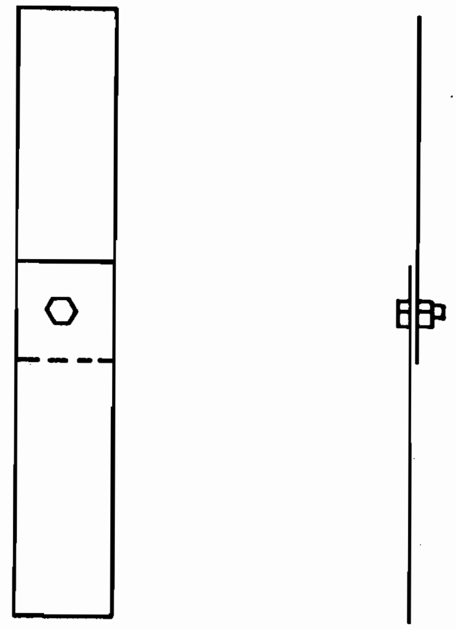

Fig. 21 Single Shear Connection

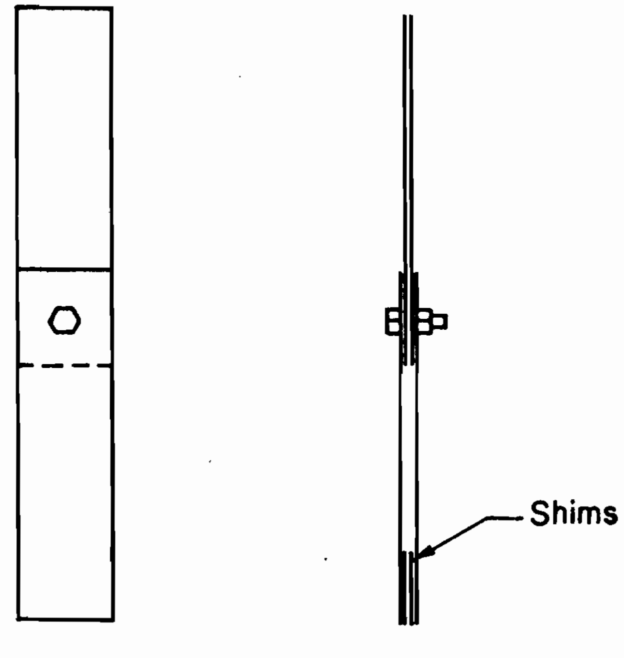

Fig. 22 Double Shear Connection

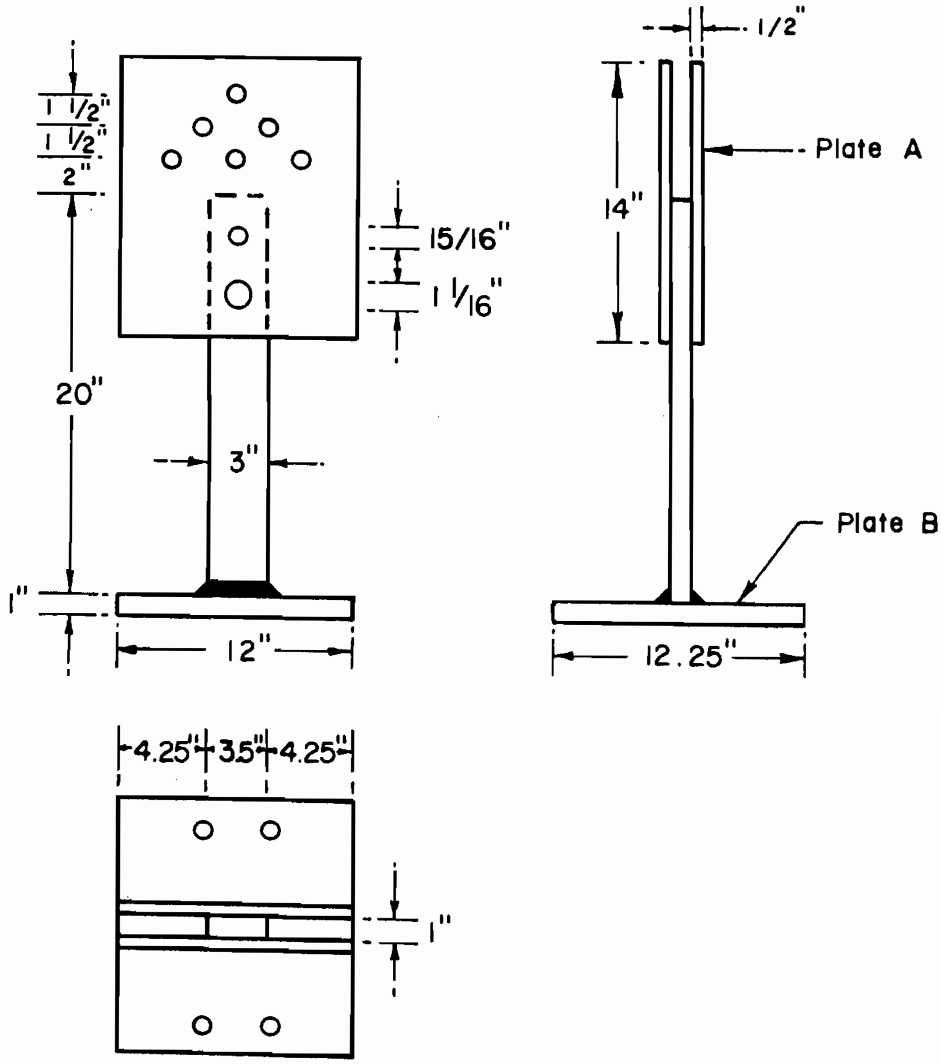

Fig. 23 Supporting Unit

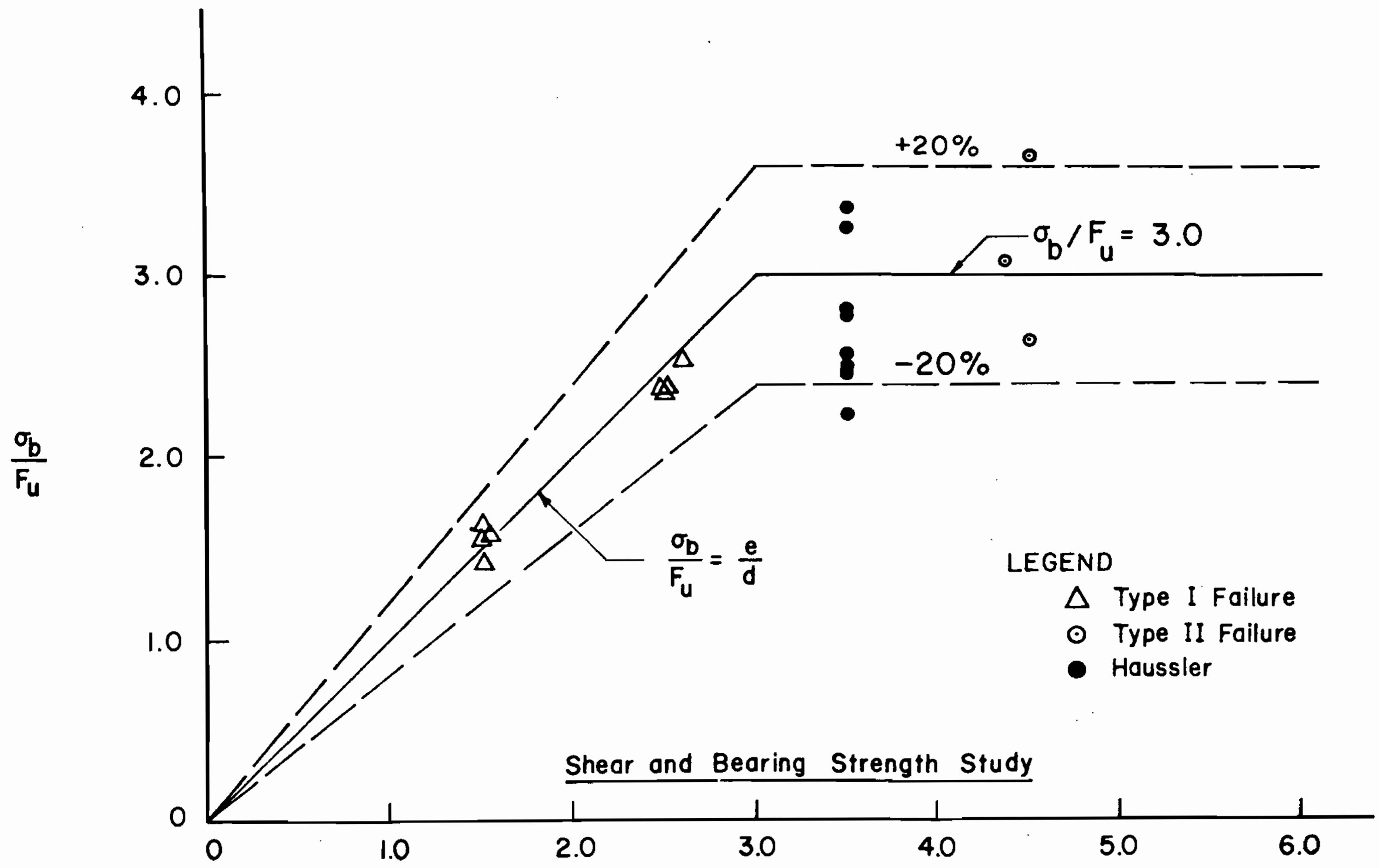

Fig. 24 Single Shear Connections with Washers, $F_u/F_y \geq 1.15$, $t \leq 0.036$ in.

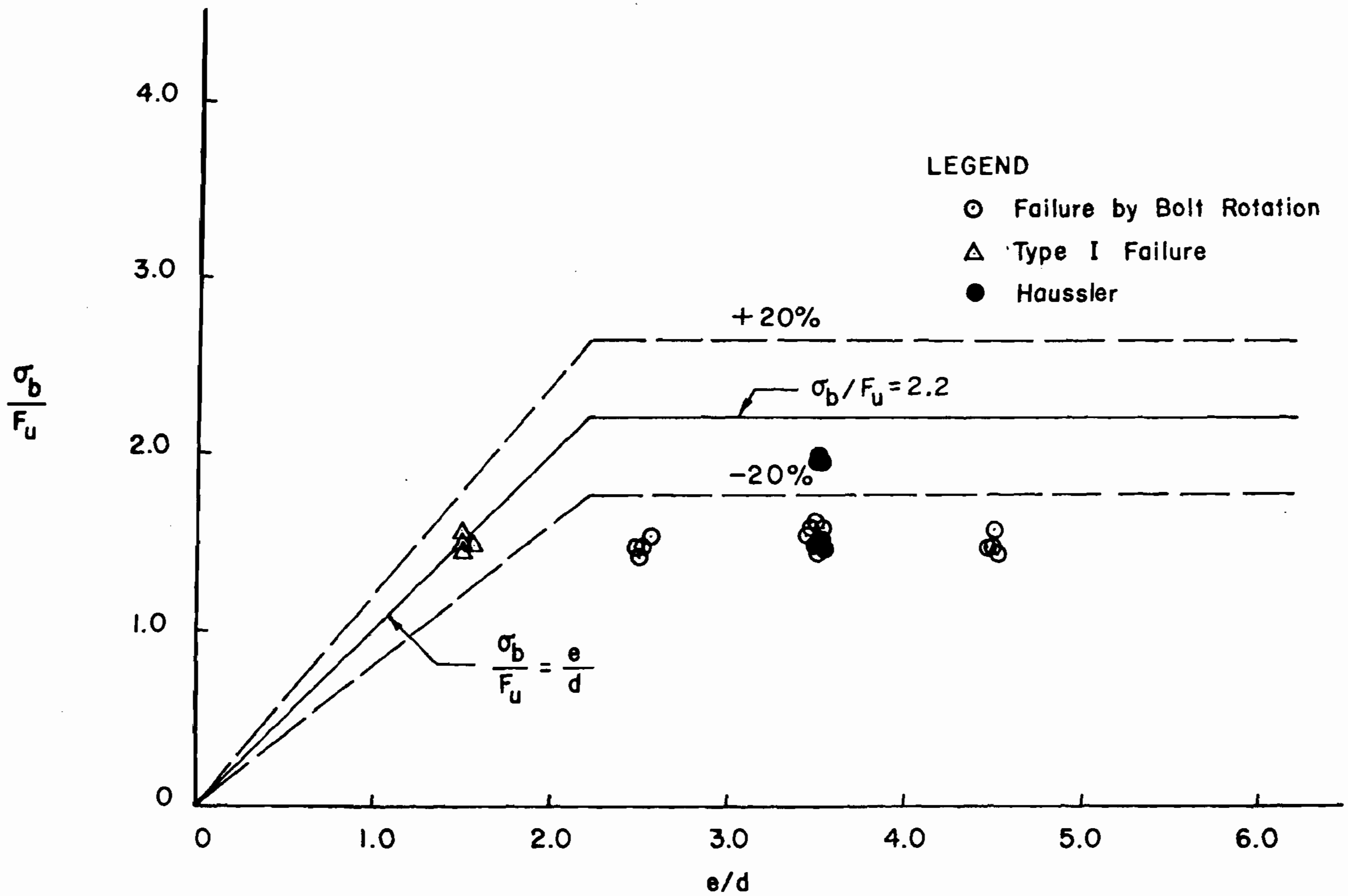

Fig. 25 Single Shear Connections without Washers, $F_u/F_y \geq 1.15$, $t \leq 0.036$ in.

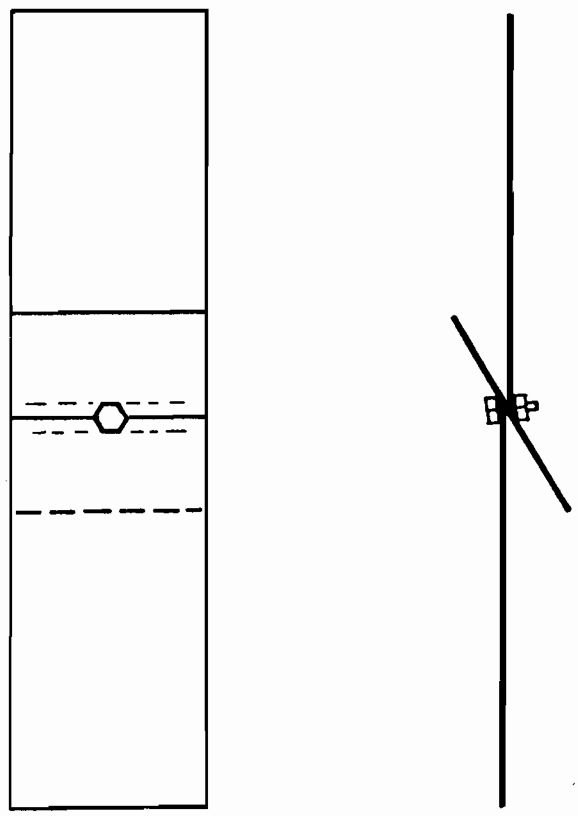

Fig. 26 Failure by Bolt Rotation
and Sheet Warping

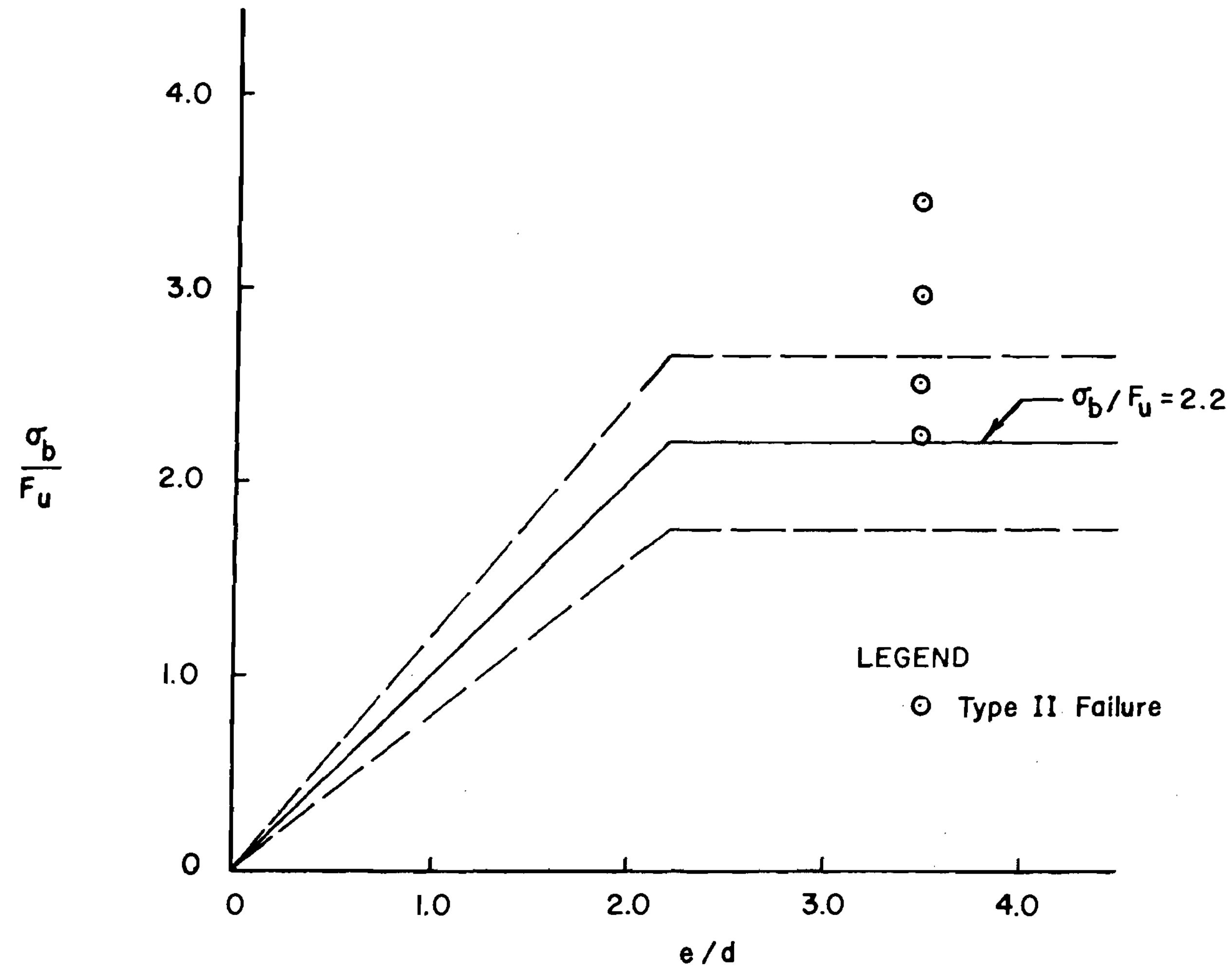

Fig. 27 Single Shear Connections Without Washers $\frac{F_u}{F_y} \geq 1.15$, $t \geq 0.036$ in.

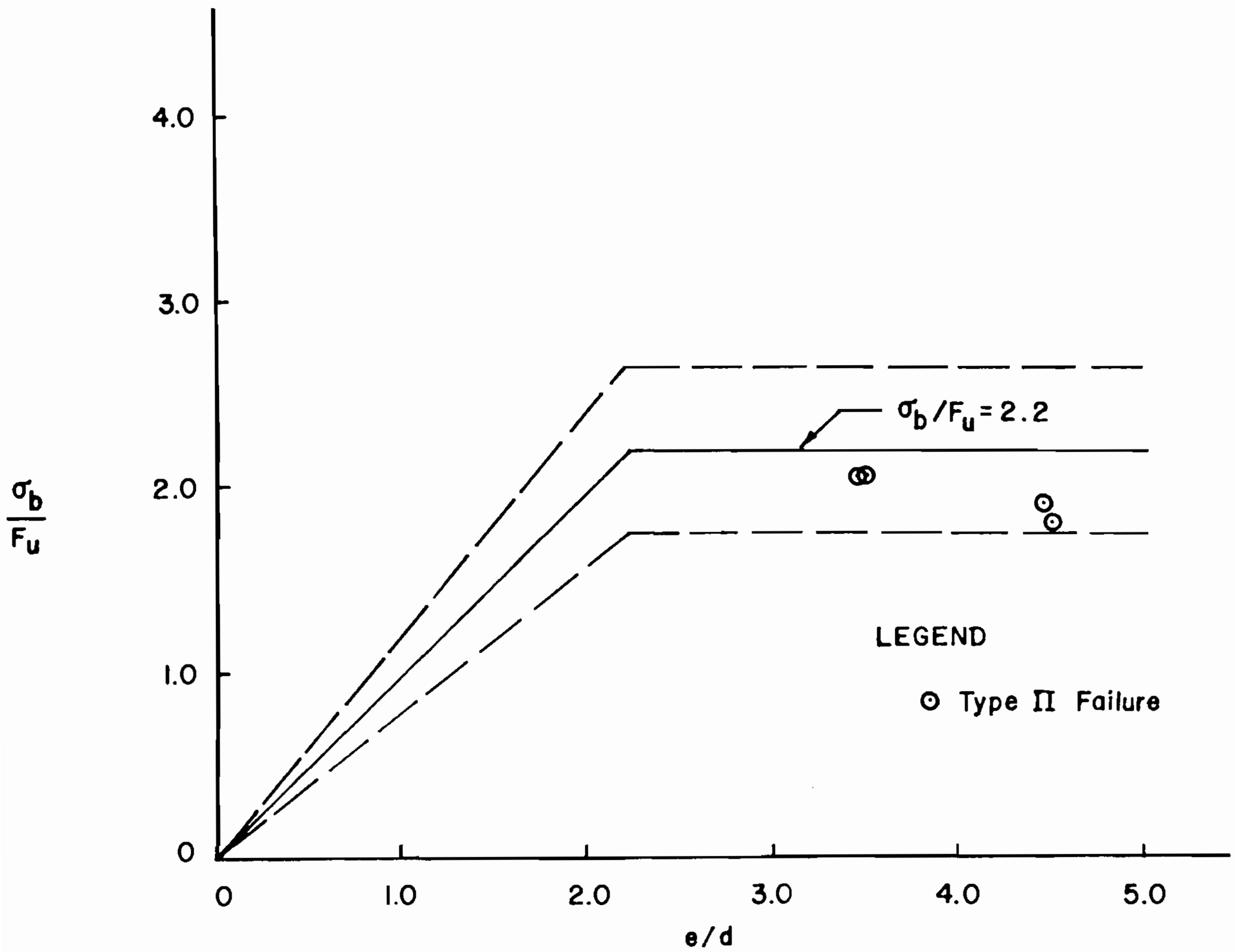

Fig. 28 Double Shear Connections Without Washers $F_u/F_y \geq 1.15$, t ≤ 0.036 in.

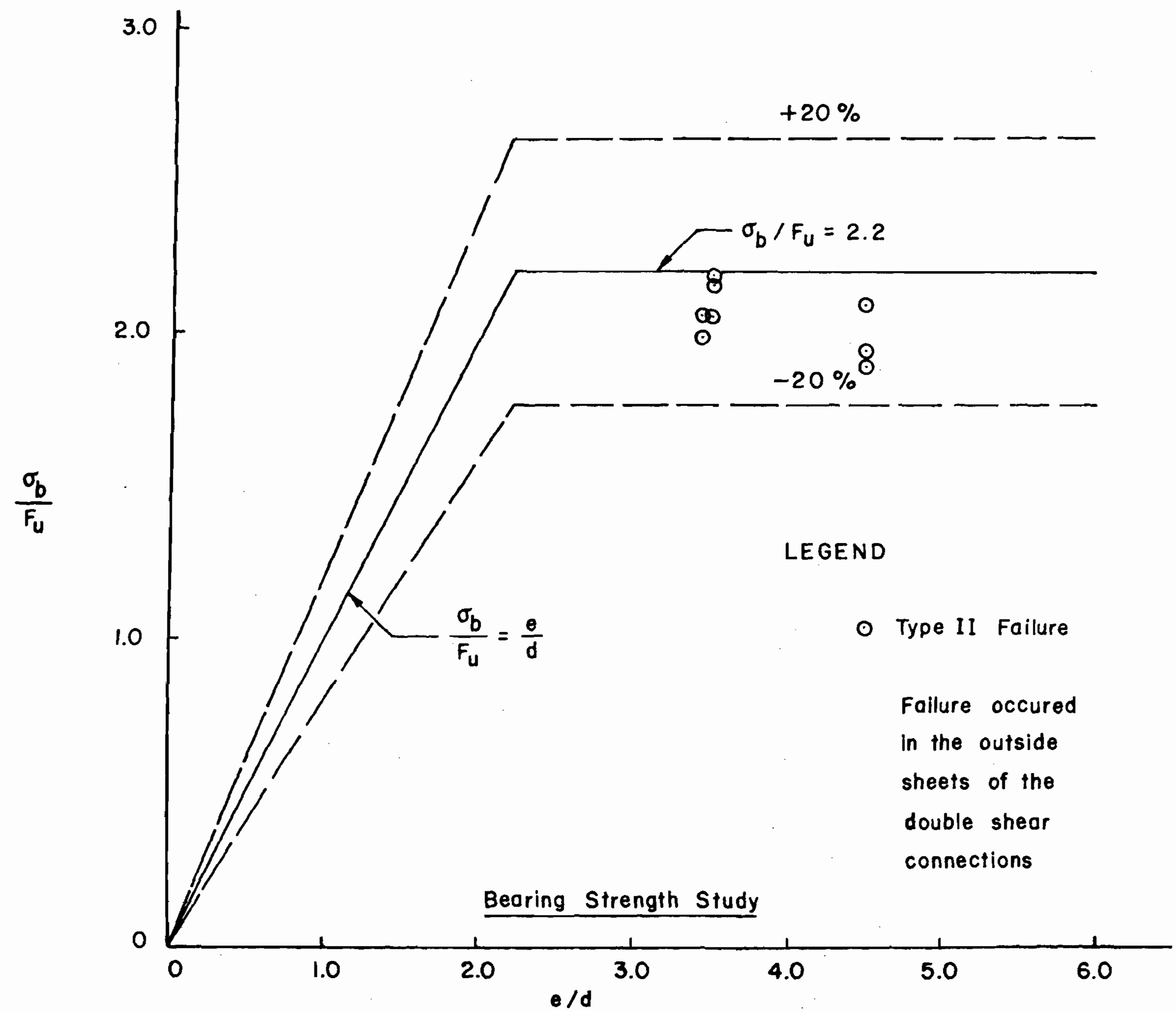

Fig. 29 Double Shear Connections without Washers, $F_u/F_y \geq 1.15$, $t \geq 0.036$ in.

Department of Civil Engineering

University of Missouri-Rolla

THIRD PROGRESS REPORT

BOLTED CONNECTIONS IN COLD-FORMED STEEL STRUCTURES

by

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Research Assistant

A Research Project Sponsored by

American Iron and Steel Institute

Rolla, Missouri August 1978

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I. INTRODUCTION

In 1976, two progress reports on bolted connections used in cold-formed steel structures were submitted to American Iron and Steel Institute (1,2). These two reports summarized the research findings which were achieved during the year of 1976.

During the year of 1977, additional bolted connection tests were conducted by Randall L. Mosby, Graduate Research Assistant in the Department of Civil Engineering at the University of Missouri-Rolla. These tests were used to study the effect of torque on the bearing strength of bolted connections.

This information is required for development of the installation procedures for bolts to be used in cold-formed steel construction.

The experimental investigation carried out at UMR during 1977 is presented in Section II of this report. It contains the discussions concerning preparation of specimens, testing of specimens, results of tests, and evaluation of the test data. The required future study is summarized in Section III.

II. EXPERIMENTAL INVESTIGATION

In the 1968 Edition of the AISI Specification for the Design of Cold-Formed Steel Structural Members (3), Section 4.5 provides the design criteria for bolted connections. It does not include any specific procedures for installation of bolts. Because the structural performance of bolted connections may be affected by the amount of torque used for installation, this phase of experimental work was planned for a study of the effect of torque on the bearing strength of bolted connections. It also considered the effect of washers on the bearing strength of connections.

The types of connections used for the tests were carefully considered by members of the AISI Task Group on Bolted Connections at its September 15, 1976 meeting. It was suggested that the following materials and parameters be used in this series of tests:

1. Types of Bolts

   Three types of bolts were suggested for this study. They include

   (a) ASTM A307 bolts (1/4" to 3/4" in diameter)

   (b) ASTM A354, Grade BD bolts (1/4" in diameter)

   (c) ASTM A490 bolts (1/2" and 3/4" in diameter)

2. Thicknesses of Steel Sheets

   The thicknesses of steel sheets were suggested to be varied from 0.015 in. to 3/16 in.

3. Yield Points and the F_u/F_y Ratios of Steel Sheets

   It was suggested that the yield points of steel sheets be varied from 33 to about 65 ksi. The range of F_u/F_y ratios should be as large as possible.

4. Torque Used for Installation

   Three types of torque were suggested for installation of bolts.

They are

(a) Zero torque (i.e. finger tight condition)

(b) Low torque

Use the lower values of torque given in Table 1(a). These values were previously used at Cornell University for installation of the A307 bolts reported in Ref. 4.

(c) High torque

Use the higher values of torque listed in Table 1(b). These values were previously used at Cornell University for installation of the high strength bolts reported in Ref. 5.

5. Washers and e/d Ratios

It was suggested that the connections be tested with and without washers.

(a) For connections with washers under both bolt head and nut, use $e/d = 3.5$, where e is the end distance measured in the line of stress from the center of a standard hole to the end of the sheet, and d is the diameter of bolt.

(b) For connections without washers, use $e/d = 2.2$.

These e/d ratios were considered to be the minimum values for the bolted connections failed in the bearing mode.

6. Types of Connections

It was also suggested that the connections be tested for

(a) Single shear condition, and

(b) Double shear condition.

A. Preparation of Test Specimens

All test specimens were composed of blanks as shown in Fig. 1. The actual dimemsions for the end distance "e" measured from the center of a standard hole* to the end of steel sheet and the width "s" are listed in Table 3a. These dimensions were designed to ensure that the test specimens would fail in bearing between the bolt and steel sheets. This was accomplished by choosing the proper dimensions so that the tensile capacity of steel sheets and the shear capacity of the bolts are greater than the bearing capacity of the connection. In order to prevent the possible longitudinal shearing failure of steel sheets, the e/d ratios are about 3.5 for connections with washers under both bolt head and nut. For the connections without washers, the e/d ratios are about 2.2.

Due to the difficulty of obtaining the exact types of materials suggested by the AISI Task Group, the test specimens were prepared by using the following available bolts and steel sheets:

1. Types of Bolts Used in the Tests

   Two types of bolts were used in the connection tests. They are ASTM A307 bolts and Grade 8 bolts (1/4", 1/2" and 3/4" in diameter). The Grade 8 bolts are high strength bolts. They were used to replace the A354 Grade BD bolts and A490 bolts. See Tables 3b to 3d for dimensions of bolts, nuts and washers.

2. Thicknesses of Steel Sheets

   The actual thicknesses of steel sheets used in the tests ranged from 0.014 to 0.184 in. See Table 2.

3. Yield points and F_u/F_y Ratios of Steel Sheets

   The actual yield points of steel sheets used in the bolted connections ranged from 38.97 to 70.64 ksi. The corresponding F_u/F_y ratios varied from 1.116 to 1.321. Table 2 lists all the mechanical properties obtained from the tests.

*The diameters of standard holes are 1/32 in. larger than the nominal size of the 1/4 in. bolt and 1/16 in. larger than the 1/2 and 3/4 in. bolts.

The test specimens were prepared for single shear and double shear conditions. Figures 2 and 3 show the configurations of the connected parts for the single and double shear connections, respectively. For each test, the type and size of bolt and the dimensions of the steel sheets are listed in Table 3a.

During preparation of test specimens, the hole diameters were drilled 1/32 in. larger than the 1/4 in. bolts, and 1/16 in. larger than the 1/2 in. and 3/4 in. bolts.

B. Testing of Specimens

A total of 370 bolted connections were tested to failure in a 200,000 pounds Tinius Olson Universal testing machine. Among these tests, 178 are single shear tests and 192 are double shear tests.

For the specimens having the widths less than 3.50 inches, the steel sheets were gripped directly by the crosshead of the testing machine. When the widths of steel sheets were wider than 3.5 inches, a specially designed supporting unit was used to connect each end of the test specimens. Figure 4 shows the dimensions of this supporting unit. Plate A, the grip plate, was designed to connect the test specimens, and plate B, the bearing plate, was connected to the crosshead of the testing machine by using four anchor bolts.

Prior to testing, the bolts were tightened to the specified torque by using a torque wrench. Three types of torque values were used for installation. They were recommended by the AISI Task Group as follows:

(a) Zero torque

(b) Low torque (Table 1a)

(c) High torque (Table 1b)

For the connections using zero torque, the bolts were first tightened to

100% of the low torque values as listed in Table 1 and then released the torque value to zero in order to flatten the steel sheets and the burrs along the edge of holes.

C. Results of Tests

The tested ultimate loads, $(P_u)_{test}$, for all the bolted connections are listed in Table 4. Based the values of $(P_u)_{test}$, the conventional tested bearing stresses, $(\sigma_b)_{test}$, can be computed by using the following formula:

$$(\sigma_b)_{test} = \frac{(P_u)test}{dt} \qquad (1)$$

in which d is the diameter of bolt and t is the thickness of steel sheet.

Also included in Table 4 are the failure modes of connections observed from the tests. The types of failure are designated as follows:

Type I - Longitudinal shearing of the steel sheets

Type II - Bearing failure between steel sheet and bolt

Type III - Transverse tension tearing of steel sheet

Type IV - Shearing of the bolt

Type V - Tearing of steel sheet caused by the excessive bolt rotation and dishing of sheet material. Figure 5 shows this type of failure mode.

D. Evaluation of Test Data

During the evaluation of test data, considerations were given to the following subjects:

- Factors of safety against bearing failure on the basis of the revised Section 4.5.6 of the AISI Specification (6).
- Effect of torque on the bearing strength of bolted connections.
- Effect of washers on the structural behavior of bolted connections.

- Design methods for thin sheets which are not covered in the revised Section 4.5.6 of the AISI Specification.

All the above listed items will be discussed in this article.

(a) Factors of Safety Against Bearing Failure on the Basis of the Revised Section 4.5.6 of the AISI Specification

In the determination of the factors of safety against bearing failure, studies have been carried out for the connections made from the steel sheets covered in the revised Section 4.5.6 of the AISI Specification. Because the newly revised design provisions on allowable bearing stress are not applicable to the steel sheets thinner than 0.024 in. and 0.036 in. for connections with and without washers, respectively, the results of connection tests were therefore divided into the following four groups for the convenience of investigation:

1. Single shear with washers ($0.024" \leq t \leq 3/16"$)

   Zero Torque

   Low Torque

   High Torque

2. Double shear with washers ($0.024" \leq t \leq 3/16"$)

   Zero Torque

   Low Torque

   High Torque

3. Single shear without washers ($0.036" \leq t < 3/16"$)

   Zero Torque

   Low Torque

   High Torque

4. Double shear without washers (0.036" $\leq t \leq$ 3/16")

   Zero Torque

   Low Torque

   High Torque

These 12 cases are listed in Tables 5a to 8c. In these tables, the allowable bearing stresses, $(\sigma_b)_{allow}$, were computed in accordance with the new revision of Section 4.5.6 of the AISI Specification as follows:

"Section 4.5.6 - Bearing Stress in Bolted Connections

The bearing stress on the area (dxt) shall not exceed the allowable stress given in Tables 4.5.6(A) and 4.5.6(B), where F_p is the allowable bearing stress, ksi, F_u and F_y are defined in Section 4.5.4. For conditions not shown, stresses shall be determined on the basis of test data using a factor of safety of 2.22."

The factors of safety were determined by the ratios of $(\sigma_b)_{test}/(\sigma_b)_{allow.}$ It has been noted that some of the low factors of safety were due to either the excessive rotation of bolts or the combined bearing and tearing. In some cases, the size of washers may affect the bearing strength of connections. The mean values and the corresponding coefficients of variation for these 12 cases are summarized in Table 9. It can be seen that if the low torque values are used for installation of unfinished and high strength bolts, the average factors of safety are 2.22 and 2.25 for single shear connections with and without washers, respectively. These values are considered to be adequate for structural design of bolted connections. For the case of double shear connections with and without washers, the new revisions of Section 4.5.6 are found to be slightly conservative. As indicated in Table 9, the use of high torque for installation of bolts has slightly increased the factors of safety and at the same time reduced the coefficients of variation.

Table 4.5.6 (A)

Allowable Bearing Stresses for Bolted Connections with Washers under both Bolt Head and Nut

Thickness of connected part (inches)	Type of joint	F_u/F_y Ratio of connected part	Allowable bearing stress, F_p (ksi)
$\geq$ 0.024 but < 3/16	Inside sheet of double shear connection	$\geq$ 1.15	1.50 F_u
		< 1.15	1.35 F_u
	Single shear and outside sheets of double shear connection	No limit	1.35 F_u
$\geq$ 3/16	See Section 4.5.1		

Table 4.5.6 (B)

Allowable Bearing Stresses for Bolted Connections without Washers under both Bolt Head and Nut, or with only One Washer

Thickness of connected part (inches)	Type of joint	F_u/F_y Ratio of connected part	Allowable bearing stress, F_p (ksi)
$\geq$ 0.036 but < 3/16	Inside sheet of double shear connection	$\geq$ 1.15	1.35 F_u
	Single shear and outside sheets of double shear connection	$\geq$ 1.15	1.00 F_u
$\geq$ 3/16	See Section 4.5.1		

(b) Effect of Torque on the Bearing Strength of Bolted Connections

In order to study the effect of torque on the bearing strength of bolted connections, the test results for the steel thicknesses ranging from 0.014 in. to 0.184 in. have been regrouped and presented in Tables 10a to 10d. In these four tables, the symbol $(\sigma_b)_O$ is the average value of two identical tests by using zero torque (or finger tight condition) for installation of bolts. $(\sigma_b)_L$ and $(\sigma_b)_H$ are the average values of two identical tests by using the low torque (Table 1a) and the high torque (Table 1b), respectively. If the low torque is considered to be the minimum required torque for installation, then for a given type of connection the ratio of $(\sigma_b)_O/(\sigma_b)_L$ would indicate the reduction of the bearing strength by using the "finger tight" condition. On the other hand, the increase of the bearing strength due to the use of high torque can be represented by the ratio of $(\sigma_b)_H/(\sigma_b)_L$.

A study of the ratios of $(\sigma_b)_O/(\sigma_b)_L$ and $(\sigma_b)_H/(\sigma_b)_L$ listed in Tables 10a to 10d indicates that the effect of torque on the bearing strength of connections varies with the d/t ratios, the type of connections (single shear or double shear condition), and the use of washers. As far as the influence of the d/t ratios is concerned, the ratio of $(\sigma_b)_O/(\sigma_b)_L$ tends to decrease as the d/t ratio increases particularly for the single and double connections with washers. This fact can be seen by observing the test data shown in Figs. 6 to 9. Based on the test results plotted on these four figures, the following four equations have been developed to determine the effects of the d/t ratios on $(\sigma_b)_O/(\sigma_b)_L$:

1. Single Shear Connections With Washers

$$\frac{(\sigma_b)_O}{(\sigma_b)_L} = 1.044 - 0.0124(\frac{d}{t}) \qquad (2)$$

2. Double Shear Connections With Washers

$$\frac{(\sigma_b)_O}{(\sigma_b)_L} = 0.966 - 0.0157\left(\frac{d}{t}\right) \tag{3}$$

3. Single Shear Connections Without Washers

$$\frac{(\sigma_b)_O}{(\sigma_b)_L} = 0.989 - 0.0070\left(\frac{d}{t}\right) \tag{4}$$

4. Double Shear Connections Without Washers

$$\frac{(\sigma_b)_O}{(\sigma_b)_L} = 0.994 - 0.0068\left(\frac{d}{t}\right) \tag{5}$$

For the case of using high torques, the $(\sigma_b)_H/(\sigma_b)_L$ ratio usually increases as the d/t ratios increase particularly for single shear connections with and without washers. The effects of the d/t ratios on $(\sigma_b)_H/(\sigma_b)_L$ are represented by the following four equations which were derived from the test data shown in Figs. 10 to 13.

1. Single Shear Connections With Washers

$$\frac{(\sigma_b)_H}{(\sigma_b)_L} = 0.843 + 0.0249\left(\frac{d}{t}\right) \tag{6}$$

2. Double Shear Connections With Washers

$$\frac{(\sigma_b)_H}{(\sigma_b)_L} = 1.010 + 0.0050\left(\frac{d}{t}\right) \tag{7}$$

3. Single Shear Connections Without Washers

$$\frac{(\sigma_b)_H}{(\sigma_b)_L} = 0.882 + 0.0193\left(\frac{d}{t}\right) \tag{8}$$

4. Double Shear Connections Without Washers

$$\frac{(\sigma_b)_H}{(\sigma_b)_L} = 1.074 - 0.0029(\frac{d}{t}) \tag{9}$$

From Fig. 13, it can be seen that even though Eq. (9) was obtained from a least square method, it appears that Eq. (7) which was derived for the case of double shear connections with washers can also be used for the case of double shear connections without washers.

Based on the above discussion and the test data presented in Tables 10a to 10d and Figs. 6 to 13, it can be seen that for some types of bolted connections with larger d/t ratios, the bearing strength may be affected by the amount of torque actually used in the installation. This means that a relatively large effect of torque on bearing strength should be expected for the thin sheets used for four types of bolted connections governed by Eqs. (2), (3), (6), and (8).

(c) Effect of Washers on the Structural Behavior of Bolted Connections

The effect of washers on the bearing strength of bolted connections was briefly studied by comparing the tested bearing stress with washers and the tested bearing stress of the same connections but without washers. The average ratios of $(\sigma_b)_{\text{with washers}}/(\sigma_b)_{\text{without washers}}$ are listed in Tables 11a and 11b for single shear connections and double shear connections, respectively. Based on the numerical comparisons given in Table 11, the following observations can be made:

1. The use of washers can increase the bearing strength of single shear connections considerably. This is possibly due to the fact that when washers were not used, the premature failures of the connections were usually caused by the excessive

rotation of the bolts followed by the bending in the lap sheets. Table 4 indicates that for the single shear connections without washers, the connections usually failed by Type V, for which the connection strength was governed by the inclination of fasteners. For this type of failure mode, the following European recommendations are being used for the design of screwed connections (7,8):

$$F_{all} = \frac{F_B}{F.S.} \tag{10}$$

where F_{all} = allowable design load (kgf)

F_B = ultimate load (kgf)

$$= k_1(d + 10)(t_2^2 + 0.22)\sigma_B \tag{11}$$

$$k_1 = 0.156\left(\frac{t_1}{t_2} - 1\right)^2 + 0.35 \leq 0.7 \tag{12}$$

t_1 = thickness of the thicker sheet (mm)

t_2 = thickness of the thinner sheet (mm)

σ_B = ultimate tensile strength of the steel sheet (kgf/mm^2)

F.S. = factor of safety

= 2.9 recommended for steel sheet

2. The effect of washers is less important for the inside sheet of double shear connections. See the average ratios of $(\sigma_b)_{with\ washers}/(\sigma_b)_{without\ washers}$ given in Table 11b.
3. For the range of thickness of steel sheets used in this experimental investigation, the effect of washers was not significantly influenced by the d/t ratios.
4. The scatters of the average ratios of $(\sigma_b)_{with\ washers}/(\sigma_b)_{without\ washers}$ are considerably large. This is possibly due

to the variation of washer sizes and the different types of failure mode. In addition, the initial dishing of thin steel sheets caused by the applied torque may reduce the bearing capacity of the connections.

(d) Design Methods for Thin Sheets Which are Not Covered in the Revised Section 4.5.6 of the AISI Specification

Based on the discussion of item (a) concerning the factors of safety against the bearing failure on the basis of the revised Section 4.5.6 of the AISI Specification, it appears that the values of low torque can be used for installation of A307 and high-strength bolts when they are used in cold-formed steel construction. Figures 14 to 20 show the correlations between the test data obtained for the condition of low torque and the corresponding formulas for predicting the ultimate bearing strength of bolted connections. In these six figures, the test data was selected for the thicknesses of steel sheets no less than 0.024 in. and 0.036 in. for connections with and without washers, respectively, because these two specific thicknesses are included in the newly revised Section 4.5.6 of the AISI Specification as the minimum values for using the design criteria.

In order to check the applicability of the ultimate bearing strength formulas for thin sheets, Figs. 21 to 23 were plotted for the connections with washers and $t < 0.024$ in. In addition, Figs. 24 to 27 were plotted for the connections without washers and $t < 0.036$ in. These figures show that the basic formulas used for the development of Section 4.5.6 of the AISI Specification can also be used for 0.014 in. steel sheets.

E. Summary

A total of 370 bolted connections have been tested to study the bearing strength of connections affected by the torque used in installation.

The test specimens were fabricated from two types of bolts, three different bolt diameters, and seven different steel sheets with various mechanical properties. The bolts were installed by using three different torques for the connections with and without washers.

All test results were carefully evaluated. It was found that for some types of bolted connections with large d/t ratios, the bearing strength may be affected by the amount of torque actually used in the installation. The use of washers can improve considerably the bearing strength of lap joints which are considered to be single shear connections. However, for the inside sheet of the butt joints which are considered to be double shear connections, the effect of washers is less important.

When the low torque values are used for installation of A307 and high-strength bolts, sufficient safety factors can be obtained by using the revised Section 4.5.6 of the AISI Specification. The results of available tests for thin sheets indicate that the revised AISI design provisions for allowable bearing stress can be used for the thicknesses of steel sheets less than that included in the Specification.

The primary objective of this phase of study was to develop an installation procedure for the bearing-type connections to be used in cold-formed steel construction. Based on the evaluation of test data presented in Article II.D of this report it may be concluded that when structural bolts are installed by using the low torque values given in Table 1a, satisfactory performance can be expected as far as the bearing capacity of the connection is concerned. The design requirements for minimum edge distance, minimum spacing, tensile capacity of net section and the shear strength of bolts will not be affected by the initial clamping force.

III. FUTURE STUDY

The future study of bolted connections may include the following subjects:

1. As shown in Fig. 28, the steel sheet may fail under the condition of combined shear and tension. This type of failure mode has been pointed out by Cedric Marsh in Ref. 9. The ultimate strength of this type of failure should be investigated.
2. When thin sheets are used for lap joints without using washers, the bearing strength of the connection may be limited by the excessive rotation of the bolt and the outward bending of steel sheets. Even though this type of failure mode for screwed connections has been considered in the European design recommendations, there is no specific design criteria in the AISI Specification for this type of failure. This subject should be studied for the connections using thin sheets.
3. Additional tests may be conducted for the bolted connections using different thicknesses of steel sheets. This is because all the lap joints tested at Cornell University and the University of Missouri-Rolla used the same steel sheets. This information will be needed for the development of a new design method discussed in Item 2 above.

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APPENDICES

Table 1 (a)

Low Torques Used in the Installation
of A307 Bolts and
High-Strength Bolts (4)

Bolt Diameter (in.)	Torque (ft - lb)
1/4	5
1/2	40
3/4	110

Table 1 (b)

High Torques Used in the Installation
of High Strength Bolts (5)

Bolt Diameter (in.)	Torque (ft - lb)
1/4	11
1/2	95
3/4	335

Table 2

Thicknesses and Mechanical Properties of
the Steel Sheets Used for Bolted Connection Tests

Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation, % (2-in. gage length)
0.014	38.97	46.95	20
0.154	70.64	80.84	22
0.031	59.22	74.51	24
0.036	39.50	48.85	34
0.071	52.43	69.28	27
0.074	48.11	53.70	26
0.184	54.16	70.69	30

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-11-1-0-SS	A307	1/4	0	Yes	0.014	0.875	2.47	3.50	17.86	38.97	46.95	1.205
B-1-11-2-0-SS	A307	1/4	0	Yes	0.014	0.906	2.50	3.63	17.86	38.97	46.95	1.205
B-1-11-3-L-SS	A307	1/4	5	Yes	0.014	0.891	2.50	3.56	17.86	38.97	46.95	1.205
B-1-11-4-L-SS	A307	1/4	5	Yes	0.014	0.875	2.48	3.50	17.86	38.97	46.95	1.205
B-1-11-5-0-SS	Grade 8	1/4	0	Yes	0.014	0.906	2.47	3.62	17.86	38.97	46.95	1.205
B-1-11-6-0-SS	Grade 8	1/4	0	Yes	0.014	0.875	2.50	3.50	17.86	38.97	46.95	1.205
B-1-11-7-L-SS	Grade 8	1/4	5	Yes	0.014	0.891	2.50	3.56	17.86	38.97	46.95	1.205
B-1-11-8-L-SS	Grade 8	1/4	5	Yes	0.014	0.875	2.47	3.50	17.86	38.97	46.95	1.205
B-1-11-9-H-SS	Grade 8	1/4	11	Yes	0.014	0.875	2.50	3.50	17.86	38.97	46.95	1.205
B-1-11-10-H-SS	Grade 8	1/4	11	Yes	0.014	0.844	2.50	3.38	17.86	38.97	46.95	1.205
B-0-12-1-0-SS	A307	1/4	0	No	0.014	0.547	1.97	2.19	17.86	38.97	46.95	1.205
B-0-12-2-0-SS	A307	1/4	0	No	0.014	0.547	1.97	2.19	17.86	38.97	46.95	1.205
B-0-12-3-L-SS	A307	1/4	5	No	0.014	0.563	1.97	2.25	17.86	38.97	46.95	1.205
B-0-12-4-L-SS	A307	1/4	5	No	0.014	0.563	1.97	2.25	17.86	38.97	46.95	1.205
B-0-12-5-0-SS	Grade 8	1/4	0	No	0.014	0.547	1.97	2.19	17.86	38.97	46.95	1.205
B-0-12-6-0-SS	Grade 8	1/4	0	No	0.014	0.563	1.97	2.25	17.86	38.97	46.95	1.205
B-0-12-7-L-SS	Grade 8	1/4	5	No	0.014	0.547	1.92	2.19	17.86	38.97	46.95	1.205
B-0-12-8-L-SS	Grade 8	1/4	5	No	0.014	0.555	1.97	2.22	17.86	38.97	46.95	1.205
B-0-12-9-H-SS	Grade 8	1/4	11	No	0.014	0.555	1.94	2.22	17.86	38.97	46.95	1.205
B-0-12-10-H-SS	Grade 8	1/4	11	No	0.014	0.563	1.97	2.25	17.86	38.97	46.95	1.205

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-13-1-0-DS	A307	1/4	0	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-13-2-0-DS	A307	1/4	0	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-13-3-L-DS	A307	1/4	5	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-13-4-L-DS	A307	1/4	5	Yes	0.014	0.860	3.25	3.44	17.86	38.97	46.95	1.205
B-1-13-5-0-DS	Grade 8	1/4	0	Yes	0.014	0.856	3.25	3.42	17.86	38.97	46.95	1.205
B-1-13-6-0-DS	Grade 8	1/4	0	Yes	0.014	0.863	3.25	3.45	17.86	38.97	46.95	1.205
B-1-13-7-L-DS	Grade 8	1/4	5	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-13-8-L-DS	Grade 8	1/4	5	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-13-9-H-DS	Grade 8	1/4	11	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-13-10-H-DS	Grade 8	1/4	11	Yes	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-1-0-DS	A307	1/4	0	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-2-0-DS	A307	1/4	0	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-3-L-DS	A307	1/4	5	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-4-L-DS	A307	1/4	5	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-5-0-DS	Grade 8	1/4	0	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-6-0-DS	Grade 8	1/4	0	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-7-L-DS	Grade 8	1/4	5	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-8-L-DS	Grade 8	1/4	5	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-9-H-DS	Grade 8	1/4	11	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-0-14-10-H-DS	Grade 8	1/4	11	No	0.014	0.875	3.25	3.50	17.86	38.97	46.95	1.205
B-1-15-1-0-SS	Grade 8	1/4	0	Yes	0.036	0.875	2.47	3.50	6.94	39.50	48.85	1.237
B-1-15-2-0-SS	Grade 8	1/4	0	Yes	0.036	0.875	2.47	3.50	6.94	39.50	48.85	1.237
B-1-15-3-L-SS	Grade 8	1/4	5	Yes	0.036	0.891	2.50	3.56	6.92	39.50	48.85	1.237
B-1-15-4-L-SS	Grade 8	1/4	5	Yes	0.036	0.875	2.47	3.50	6.94	39.50	48.85	1.237
B-1-15-5-H-SS	Grade 8	1/4	11	Yes	0.036	0.875	2.47	3.50	6.94	39.50	48.85	1.237
B-1-15-6-H-SS	Grade 8	1/4	11	Yes	0.036	0.875	2.50	3.50	6.94	39.50	48.85	1.237

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-16-1-0-SS	A307	1/2	0	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-2-0-SS	A307	1/2	0	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-3-L-SS	A307	1/2	40	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-4-L-SS	A307	1/2	40	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-5-0-SS	Grade 8	1/2	0	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-6-0-SS	Grade 8	1/2	0	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-7-L-SS	Grade 8	1/2	40	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-8-L-SS	Grade 8	1/2	40	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-9-H-SS	Grade 8	1/2	95	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-1-16-10-H-SS	Grade 8	1/2	95	Yes	0.036	1.75	4.0	3.50	13.89	39.50	48.85	1.237
B-0-17-1-0-SS	A307	1/4	0	No	0.036	0.563	1.97	2.25	6.94	39.50	48.85	1.237
B-0-17-2-0-SS	A307	1/4	0	No	0.036	0.563	1.97	2.25	6.94	39.50	48.85	1.237
B-0-17-3-L-SS	A307	1/4	5	No	0.036	0.563	2.00	2.25	6.94	39.50	48.85	1.237
B-0-17-4-L-SS	A307	1/4	5	No	0.036	0.563	1.97	2.25	6.94	39.50	48.85	1.237
B-0-17-5-0-SS	Grade 8	1/4	0	No	0.036	0.563	1.97	2.25	6.94	39.50	48.85	1.237
B-0-17-6-0-SS	Grade 8	1/4	0	No	0.036	0.547	1.97	2.19	6.94	39.50	48.85	1.237
B-0-17-7-L-SS	Grade 8	1/4	5	No	0.036	0.563	1.97	2.25	6.94	39.50	48.85	1.237
B-0-17-8-L-SS	Grade 8	1/4	5	No	0.036	0.563	1.97	2.25	6.94	39.50	48.85	1.237
B-0-17-9-H-SS	Grade 8	1/4	11	No	0.036	0.563	2.00	2.25	6.94	39.50	48.85	1.237
B-0-17-10-H-SS	Grade 8	1/4	11	No	0.036	0.550	1.97	2.20	6.94	39.50	48.85	1.237

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-18-1-0-SS	A307	1/2	0	No	0.036	1.094	3.00	2.188	13.89	39.50	48.85	1.237
B-0-18-2-0-SS	A307	1/2	0	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-3-L-SS	A307	1/2	40	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-4-L-SS	A307	1/2	40	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-5-0-SS	Grade 8	1/2	0	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-6-0-SS	Grade 8	1/2	0	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-7-L-SS	Grade 8	1/2	40	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-8-L-SS	Grade 8	1/2	40	No	0.036	1.125	3.00	2.250	13.89	39.50	48.85	1.237
B-0-18-9-H-SS	Grade 8	1/2	95	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-0-18-10-H-SS	Grade 8	1/2	95	No	0.036	1.100	3.00	2.200	13.89	39.50	48.85	1.237
B-1-19-1-0-DS	A307	1/4	0	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-2-0-DS	A307	1/4	0	Yes	0.036	0.891	3.25	3.56	6.94	39.50	48.85	1.237
B-1-19-3-L-DS	A307	1/4	5	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-4-L-DS	A307	1/4	5	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-5-0-DS	Grade 8	1/4	0	Yes	0.036	0.891	3.25	3.56	6.94	39.50	48.85	1.237
B-1-19-6-0-DS	Grade 8	1/4	0	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-7-L-DS	Grade 8	1/4	5	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-8-L-DS	Grade 8	1/4	5	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-9-H-DS	Grade 8	1/4	11	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237
B-1-19-10-H-DS	Grade 8	1/4	11	Yes	0.036	0.875	3.25	3.50	6.94	39.50	48.85	1.237

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-20-1-0-DS	A307	1/2	0	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-2-0-DS	A307	1/2	0	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-3-L-DS	A307	1/2	40	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-4-L-DS	A307	1/2	40	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-5-0-DS	Grade 8	1/2	0	Yes	0.036	1.813	6.25	3.625	13.89	39.50	48.85	1.237
B-1-20-6-0-DS	Grade 8	1/2	0	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-8-L-DS	Grade 8	1/2	40	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-9-H-DS	Grade 8	1/2	95	Yes	0.036	1.78	6.25	3.50	13.89	39.50	48.85	1.237
B-1-20-10-H-DS	Grade 8	1/2	95	Yes	0.036	1.75	6.25	3.50	13.89	39.50	48.85	1.237
B-0-21-1-0-DS	A307	1/4	0	No	0.036	0.844	3.25	3.38	6.94	39.5	48.85	1.237
B-0-21-2-0-DS	A307	1/4	0	No	0.036	0.875	3.25	3.50	6.94	39.5	48.85	1.237
B-0-21-3-L-DS	A307	1/4	5	No	0.036	0.891	3.25	3.56	6.94	39.5	48.85	1.237
B-0-21-4-L-DS	A307	1/4	5	No	0.036	0.875	3.25	3.50	6.94	39.5	48.85	1.237
B-0-21-5-0-DS	Grade 8	1/4	0	No	0.036	0.875	3.25	3.50	6.94	39.5	48.85	1.237
B-0-21-6-0-DS	Grade 8	1/4	0	No	0.036	0.906	3.25	3.62	6.94	39.5	48.85	1.237
B-0-21-7-L-DS	Grade 8	1/4	5	No	0.036	0.275	3.25	3.50	6.94	39.5	48.85	1.237
B-0-21-8-L-DS	Grade 8	1/4	5	No	0.036	0.875	3.25	3.50	6.94	39.5	48.85	1.237
B-0-21-9-H-DS	Grade 8	1/4	11	No	0.036	0.875	3.25	3.50	6.94	39.5	48.85	1.237
B-0-21-10-H-DS	Grade 8	1/4	11	No	0.036	0.875	3.25	3.50	6.94	39.5	48.85	1.237

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-22-1-0-DS	A307	1/2	0	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-2-0-DS	A307	1/2	0	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-3-L-DS	A307	1/2	40	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-4-L-DS	A307	1/2	40	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-5-0-DS	Grade 8	1/2	0	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-6-0-DS	Grade 8	1/2	0	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-7-L-DS	Grade 8	1/2	40	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-8-L-DS	Grade 8	1/2	40	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-9-H-DS	Grade 8	1/2	95	No	0.036	1.75	6.25	3.50	13.89	39.5	48.85	1.237
B-0-22-10-H-DS	Grade 8	1/2	95	No	0.036	1.78	6.25	3.56	13.89	39.5	48.85	1.237
B-1-23-1-0-SS	Grade 8	1/2	0	Yes	0.074	1.75	4.00	3.50	6.757	48.11	53.70	1.116
B-1-23-2-0-SS	Grade 8	1/2	0	Yes	0.074	1.75	4.00	3.50	6.757	48.11	53.70	1.116
B-1-23-3-L-SS	Grade 8	1/2	40	Yes	0.074	1.75	4.00	3.50	6.757	48.11	53.70	1.116
B-1-23-4-L-SS	Grade 8	1/2	40	Yes	0.074	1.75	4.00	3.50	6.757	48.11	53.70	1.116
B-1-23-5-H-SS	Grade 8	1/2	95	Yes	0.074	1.75	4.00	3.50	6.757	48.11	53.70	1.116
B-1-23-6-H-SS	Grade 8	1/2	95	Yes	0.074	1.75	4.00	3.50	6.757	48.11	53.70	1.116
B-1-24-1-0-SS	A307	3/4	0	Yes	0.074	2.69	5.25	3.58	10.135	48.11	53.70	1.116
B-1-24-2-0-SS	A307	3/4	0	Yes	0.074	2.69	5.25	3.58	10.135	48.11	53.70	1.116
B-1-24-3-L-SS	A307	3/4	110	Yes	0.074	2.66	5.25	3.54	10.135	48.11	53.70	1.116
B-1-24-4-L-SS	A307	3/4	110	Yes	0.074	2.66	5.25	3.54	10.135	48.11	53.70	1.116
B-1-24-5-0-SS	Grade 8	3/4	0	Yes	0.074	2.66	5.25	3.54	10.135	48.11	53.70	1.116
B-1-24-6-0-SS	Grade 8	3/4	0	Yes	0.074	2.66	5.25	3.54	10.135	48.11	53.70	1.116
B-1-24-7-L-SS	Grade 8	3/4	110	Yes	0.074	2.69	5.25	3.58	10.135	48.11	53.70	1.116
B-1-24-8-L-SS	Grade 8	3/4	110	Yes	0.074	2.63	5.25	3.50	10.135	48.11	53.70	1.116
B-1-24-9-H-SS	Grade 8	3/4	335	Yes	0.074	2.63	5.25	3.50	10.135	48.11	53.70	1.116
B-1-24-10-H-SS	Grade 8	3/4	335	Yes	0.074	2.66	5.25	3.54	10.135	48.11	53.70	1.116

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-25-1-0-SS	Grade 8	1/2	0	No	0.074	1.10	3.00	2.20	6.757	48.11	53.70	1.116
B-0-25-2-0-SS	Grade 8	1/2	0	No	0.074	1.10	3.00	2.20	6.757	48.11	53.70	1.116
B-0-25-3-L-SS	Grade 8	1/2	40	No	0.074	1.10	3.00	2.20	6.757	48.11	53.70	1.116
B-0-25-4-L-SS	Grade 8	1/2	40	No	0.074	1.10	3.00	2.20	6.757	48.11	53.70	1.116
B-0-25-5-H-SS	Grade 8	1/2	95	No	0.074	1.10	3.00	2.20	6.757	48.11	53.70	1.116
B-0-25-6-H-SS	Grade 8	1/2	95	No	0.074	1.10	3.00	2.20	6.757	48.11	53.70	1.116
B-0-26-1-0-SS	A307	3/4	0	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-2-0-SS	A307	3/4	0	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-3-L-SS	A307	3/4	110	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-4-L-SS	A307	3/4	110	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-5-0-SS	Grade 8	3/4	0	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-6-0-SS	Grade 8	3/4	0	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-7-L-SS	Grade 8	3/4	110	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-8-L-SS	Grade 8	3/4	110	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-9-H-SS	Grade 8	3/4	335	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-0-26-10-H-SS	Grade 8	3/4	335	No	0.074	1.65	4.20	2.20	10.135	48.11	53.70	1.116
B-1-27-1-0-DS	A307	1/2	0	Yes	0.074	1.875	6.50	3.75	6.757	48.11	53.70	1.116
B-1-27-2-0-DS	A307	1/2	0	Yes	0.074	1.813	6.50	3.63	6.757	48.11	53.70	1.116
B-1-27-3-L-DS	A307	1/2	40	Yes	0.074	1.875	6.50	3.75	6.757	48.11	53.70	1.116
B-1-27-4-L-DS	A307	1/2	40	Yes	0.074	1.906	6.50	3.81	6.757	48.11	53.70	1.116
B-1-27-5-0-DS	Grade 8	1/2	0	Yes	0.074	1.813	6.50	3.63	6.757	48.11	53.70	1.116
B-1-27-6-0-DS	Grade 8	1/2	0	Yes	0.074	1.813	6.50	3.63	6.757	48.11	53.70	1.116
B-1-27-7-L-DS	Grade 8	1/2	40	Yes	0.074	1.813	6.50	3.63	6.757	48.11	53.70	1.116
B-1-27-8-L-DS	Grade 8	1/2	40	Yes	0.074	1.780	6.50	3.56	6.757	48.11	53.70	1.116
B-1-27-9-H-DS	Grade 8	1/2	95	Yes	0.074	1.840	6.50	3.68	6.757	48.11	53.70	1.116
B-1-27-10-H-DS	Grade 8	1/2	95	Yes	0.074	1.875	6.50	3.75	6.757	48.11	53.70	1.116

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-28-1-0-DS	A307	3/4	0	Yes	0.074	2.470	10.00	3.29	10.135	48.11	53.70	1.116
B-1-28-2-0-DS	A307	3/4	0	Yes	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-1-28-3-L-DS	A307	3/4	110	Yes	0.074	2.500	10.00	3.33	10.135	48.11	53.70	1.116
B-1-28-4-L-DS	A307	3/4	110	Yes	0.074	2.470	10.00	3.29	10.135	48.11	53.70	1.116
B-1-28-5-0-DS	Grade 8	3/4	0	Yes	0.074	2.625	10.00	3.50	10.135	48.11	53.70	1.116
B-1-28-6-0-DS	Grade 8	3/4	0	Yes	0.074	2.656	10.00	3.54	10.135	48.11	53.70	1.116
B-1-28-7-L-DS	Grade 8	3/4	110	Yes	0.074	2.625	10.00	3.50	10.135	48.11	53.70	1.116
B-1-28-8-L-DS	Grade 8	3/4	110	Yes	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-1-28-9-H-DS	Grade 8	3/4	335	Yes	0.074	2.625	10.00	3.50	10.135	48.11	53.70	1.116
B-1-28-10-H-DS	Grade 8	3/4	335	Yes	0.074	2.656	10.00	3.54	10.135	48.11	53.70	1.116
B-0-29-1-0-DS	A307	1/2	0	No	0.074	1.813	6.50	3.63	6.757	48.11	53.70	1.116
B-0-29-2-0-DS	A307	1/2	0	No	0.074	1.781	6.50	3.56	6.757	48.11	53.70	1.116
B-0-29-3-L-DS	A307	1/2	40	No	0.074	1.750	6.50	3.50	6.757	48.11	53.70	1.116
B-0-29-4-L-DS	A307	1/2	40	No	0.074	1.813	6.50	3.63	6.757	48.11	53.70	1.116
B-0-29-5-0-DS	Grade 8	1/2	0	No	0.074	1.844	6.50	3.69	6.757	48.11	53.70	1.116
B-0-29-6-0-DS	Grade 8	1/2	0	No	0.074	1.844	6.50	3.69	6.757	48.11	53.70	1.116
B-0-29-7-L-DS	Grade 8	1/2	40	No	0.074	1.781	6.50	3.56	6.757	48.11	53.70	1.116
B-0-29-8-L-DS	Grade 8	1/2	40	No	0.074	1.844	6.50	3.69	6.757	48.11	53.70	1.116
B-0-29-9-H-DS	Grade 8	1/2	95	No	0.074	1.844	6.50	3.69	6.757	48.11	53.70	1.116
B-0-29-10-H-DS	Grade 8	1/2	95	No	0.074	1.844	6.50	3.69	6.757	4b.11	53.70	1.116

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-30-1-0-DS	A307	3/4	0	No	0.074	2.470	10.00	3.29	10.135	48.11	53.70	1.116
B-0-30-2-0-DS	A307	3/4	0	No	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-0-30-3-L-DS	A307	3/4	110	No	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-0-30-4-L-DS	A307	3/4	110	No	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-0-30-5-0-DS	Grade 8	3/4	0	No	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-0-30-6-0-DS	Grade 8	3/4	0	No	0.074	2.530	10.00	3.38	10.135	48.11	53.70	1.116
B-0-30-7-L-DS	Grade 8	3/4	110	No	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-0-30-8-L-DS	Grade 8	3/4	110	No	0.074	2.563	10.00	3.42	10.135	48.11	53.70	1.116
B-0-30-9-H-DS	Grade 8	3/4	335	No	0.074	2.470	10.00	3.29	10.135	48.11	53.70	1.116
B-0-30-10-H-DS	Grade 8	3/4	335	No	0.074	2.470	10.00	3.29	10.135	48.11	53.70	1.116
B-1-31-1-0-SS	A307	1/4	0	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-2-0-SS	A307	1/4	0	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-3-L-SS	A307	1/4	5	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-4-L-SS	A307	1/4	5	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-5-0-SS	Grade 8	1/4	0	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-6-0-SS	Grade 8	1/4	0	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-7-L-SS	Grade 8	1/4	5	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-8-L-SS	Grade 8	1/4	5	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-9-H-SS	Grade 8	1/4	11	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144
B-1-31-10-H-SS	Grade 8	1/4	11	Yes	0.0154	0.875	2.50	3.50	16.234	70.64	80.84	1.144

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-32-1-0-SS	A307	1/4	0	No	0.0154	0.550	2.00	2.20	16.234	70.64	80.84	1.144
B-0-32-2-0-SS	A307	1/4	0	No	0.0154	0.530	2.00	2.12	16.234	70.64	80.84	1.144
B-0-32-3-L-SS	A307	1/4	5	No	0.0154	0.550	2.00	2.20	16.234	70.64	80.84	1.144
B-0-32-4-L-SS	A307	1/4	5	No	0.0154	0.550	2.00	2.20	16.234	70.64	80.84	1.144
B-0-32-5-0-SS	Grade 8	1/4	0	No	0.0154	0.550	2.00	2.20	16.234	70.64	80.84	1.144
B-0-32-6-0-SS	Grade 8	1/4	0	No	0.0154	0.560	2.00	2.25	16.234	70.64	80.84	1.144
B-0-32-7-L-SS	Grade 8	1/4	5	No	0.0154	0.550	2.00	2.20	16.234	70.64	80.84	1.144
B-0-32-8-L-SS	Grade 8	1/4	5	No	0.0154	0.560	2.00	2.25	16.234	70.64	80.84	1.144
B-0-32-9-H-SS	Grade 8	1/4	11	No	0.0154	0.560	2.00	2.25	16.234	70.64	80.84	1.144
B-0-32-10-H-SS	Grade 8	1/4	11	No	0.0154	0.550	2.00	2.20	16.234	70.64	80.84	1.144
B-1-33-1-0-DS	A307	1/4	0	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-2-0-DS	A307	1/4	0	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-3-L-DS	A307	1/4	5	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-4-L-DS	A307	1/4	5	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-5-0-DS	Grade 8	1/4	0	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-6-0-DS	Grade 8	1/4	0	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-7-L-DS	Grade 8	1/4	5	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-8-L-DS	Grade 8	1/4	5	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-9-H-DS	Grade 8	1/4	11	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-33-10-H-DS	Grade 8	1/4	11	Yes	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-34-1-0-DS	A307	1/4	0	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-2-0-DS	A307	1/4	0	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-3-L-DS	A307	1/4	5	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-4-L-DS	A307	1/4	5	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-5-0-DS	Grade 8	1/4	0	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-6-0-DS	Grade 8	1/4	0	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-7-L-DS	Grade 8	1/4	5	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-8-L-DS	Grade 8	1/4	5	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-9-H-DS	Grade 8	1/4	11	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-0-34-10-H-DS	Grade 8	1/4	11	No	0.0154	0.875	3.25	3.50	16.234	70.64	80.84	1.144
B-1-35-1-0-SS	Grade 8	1/4	0	Yes	0.031	0.875	2.25	3.50	8.065	59.22	74.51	1.258
B-1-35-2-0-SS	Grade 8	1/4	0	Yes	0.031	0.875	2.25	3.50	8.065	59.22	74.51	1.258
B-1-35-3-L-SS	Grade 8	1/4	5	Yes	0.031	0.875	2.25	3.50	8.065	59.22	74.51	1.258
B-1-35-4-L-SS	Grade 8	1/4	5	Yes	0.031	0.875	2.25	3.50	8.065	59.22	74.51	1.258
B-1-35-5-H-SS	Grade 8	1/4	11	Yes	0.031	0.875	2.25	3.50	8.065	59.22	74.51	1.258
B-1-35-6-H-SS	Grade 8	1/4	11	Yes	0.031	0.875	2.25	3.50	8.065	59.22	74.51	1.258
B-1-36-1-0-SS	A307	1/2	0	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-2-0-SS	A307	1/2	0	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-3-L-SS	A307	1/2	40	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-4-L-SS	A307	1/2	40	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-5-0-SS	Grade 8	1/2	0	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-6-0-SS	Grade 8	1/2	0	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-7-L-SS	Grade 8	1/2	40	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-8-L-SS	Grade 8	1/2	40	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-9-H-SS	Grade 8	1/2	95	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258
B-1-36-10-H-SS	Grade 8	1/2	95	Yes	0.031	1.75	4.25	3.50	16.129	59.22	74.51	1.258

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-37-1-0-SS	Grade 8	1/4	0	No	0.031	0.55	2.25	2.20	8.065	59.22	74.51	1.258
B-0-37-2-0-SS	Grade 8	1/4	0	No	0.031	0.55	2.25	2.20	8.065	59.22	74.51	1.258
B-0-37-3-L-SS	Grade 8	1/4	5	No	0.031	0.55	2.25	2.20	8.065	59.22	74.51	1.258
B-0-37-4-L-SS	Grade 8	1/4	5	No	0.031	0.55	2.25	2.20	8.065	59.22	74.51	1.258
B-0-37-5-H-SS	Grade 8	1/4	11	No	0.031	0.55	2.25	2.20	8.065	59.22	74.51	1.258
B-0-37-6-H-SS	Grade 8	1/4	11	No	0.031	0.55	2.25	2.20	8.065	59.22	74.51	1.258
B-0-38-1-0-SS	A307	1/2	0	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-2-0-SS	A307	1/2	0	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-3-L-SS	A307	1/2	40	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-4-L-SS	A307	1/2	40	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-5-0-SS	Grade 8	1/2	0	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-6-0-SS	Grade 8	1/2	0	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-7-L-SS	Grade 8	1/2	40	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-8-L-SS	Grade 8	1/2	40	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-9-H-SS	Grade 8	1/2	95	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-0-38-10-H-SS	Grade 8	1/2	95	No	0.031	1.10	3.0	2.20	16.129	59.22	74.51	1.258
B-1-39-1-0-DS	Grade 8	1/4	0	Yes	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-1-39-2-0-DS	Grade 8	1/4	0	Yes	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-1-39-3-L-DS	Grade 8	1/4	5	Yes	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-1-39-4-L-DS	Grade 8	1/4	5	Yes	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-1-39-5-H-DS	Grade 8	1/4	11	Yes	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-40-1-0-DS	A307	1/2	0	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-2-0-DS	A307	1/2	0	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-3-L-DS	A307	1/2	40	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-4-L-DS	A307	1/2	40	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-5-0-DS	Grade 8	1/2	0	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-6-0-DS	Grade 8	1/2	0	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-7-L-DS	Grade 8	1/2	40	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-8-L-DS	Grade 8	1/2	40	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-9-H-DS	Grade 8	1/2	95	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-1-40-10-H-DS	Grade 8	1/2	95	Yes	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-41-1-0-DS	Grade 8	1/4	0	No	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-0-41-2-0-DS	Grade 8	1/4	0	No	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-0-41-3-L-DS	Grade 8	1/4	5	No	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-0-41-4-L-DS	Grade 8	1/4	5	No	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-0-41-5-H-DS	Grade 8	1/4	11	No	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-0-41-6-H-DS	Grade 8	1/4	11	No	0.031	0.875	3.25	3.50	8.065	59.22	74.51	1.258
B-0-42-1-0-DS	A307	1/2	0	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-2-0-DS	A307	1/2	0	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-3-L-DS	A307	1/2	5	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-4-L-DS	A307	1/2	5	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-5-0-DS	Grade 8	1/2	0	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-6-0-DS	Grade 8	1/2	0	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-7-L-DS	Grade 8	1/2	5	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-8-L-DS	Grade 8	1/2	5	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-9-H-DS	Grade 8	1/2	11	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258
B-0-42-10-H-DS	Grade 8	1/2	11	No	0.031	1.75	6.50	3.50	16.129	59.22	74.51	1.258

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-43-1-0-SS	Grade 8	1/2	0	Yes	0.071	1.656	4.25	3.13	7.042	52.43	69.28	1.321
B-1-43-2-0-SS	Grade 8	1/2	0	Yes	0.071	1.688	4.25	3.38	7.042	52.43	69.28	1.321
B-1-43-3-L-SS	Grade 8	1/2	40	Yes	0.071	1.688	4.25	3.38	7.042	52.43	69.28	1.321
B-1-43-4-L-SS	Grade 8	1/2	40	Yes	0.071	1.688	4.25	3.38	7.042	52.43	69.28	1.321
B-1-43-5-H-SS	Grade 8	1/2	95	Yes	0.071	1.703	4.25	3.41	7.042	52.43	69.28	1.321
B-1-43-6-H-SS	Grade 8	1/2	95	Yes	0.071	1.719	4.25	3.44	7.042	52.43	69.28	1.321
B-1-44-1-0-SS	A307	3/4	0	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-3-L-SS	A307	3/4	110	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-4-L-SS	A307	3/4	110	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-5-0-SS	Grade 8	3/4	0	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-6-0-SS	Grade 8	3/4	0	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-7-L-SS	Grade 8	3/4	110	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-8-L-SS	Grade 8	3/4	110	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-9-H-SS	Grade 8	3/4	335	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-1-44-10-H-SS	Grade 8	3/4	335	Yes	0.071	2.625	6.0	3.50	10.563	52.43	69.28	1.321
B-0-45-1-0-SS	Grade 8	1/2	0	No	0.071	1.188	3.0	2.38	7.042	52.43	69.28	1.321
B-0-45-2-0-SS	Grade 8	1/2	0	No	0.071	1.10	3.0	2.20	7.042	52.43	69.28	1.321
B-0-45-3-L-SS	Grade 8	1/2	40	No	0.071	1.10	3.0	2.20	7.042	52.43	69.28	1.321
B-0-45-4-L-SS	Grade 8	1/2	40	No	0.071	1.15	3.0	2.30	7.042	52.43	69.28	1.321
B-0-45-5-H-SS	Grade 8	1/2	95	No	0.071	1.15	3.0	2.30	7.042	52.43	69.28	1.321
B-0-45-6-H-SS	Grade 8	1/2	95	No	0.071	1.10	3.0	2.20	7.042	52.43	69.28	1.321

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens (Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-46-1-0-SS	A307	3/4	0	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-2-0-SS	A307	3/4	0	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-3-L-SS	A307	3/4	110	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-4-L-SS	A307	3/4	110	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-5-0-SS	Grade 8	3/4	0	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-6-0-SS	Grade 8	3/4	0	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-7-L-SS	Grade 8	3/4	110	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-8-L-SS	Grade 8	3/4	110	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-9-H-SS	Grade 8	3/4	335	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-0-46-10-H-SS	Grade 8	3/4	335	No	0.071	1.65	4.25	2.20	10.563	52.43	69.28	1.321
B-1-47-1-0-DS	Grade 8	1/2	0	Yes	0.071	1.813	6.875	3.63	7.042	52.43	69.28	1.321
B-1-47-2-0-DS	Grade 8	1/2	0	Yes	0.071	1.813	6.875	3.63	7.042	52.43	69.28	1.321
B-1-47-3-L-DS	Grade 8	1/2	40	Yes	0.071	1.750	6.700	3.50	7.042	52.43	69.28	1.321
B-1-47-4-L-DS	Grade 8	1/2	40	Yes	0.071	1.781	6.700	3.56	7.042	52.43	69.28	1.321
B-1-47-5-H-DS	Grade 8	1/2	95	Yes	0.071	1.813	6.700	3.63	7.042	52.43	69.28	1.321
B-1-48-1-0-DS	A307	3/4	0	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-2-0-DS	A307	3/4	0	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-3-L-DS	A307	3/4	110	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-4-L-DS	A307	3/4	110	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-5-0-DS	Grade 8	3/4	0	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-6-0-DS	Grade 8	3/4	0	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-7-L-DS	Grade 8	3/4	110	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-8-L-DS	Grade 8	3/4	110	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-9-H-DS	Grade 8	3/4	335	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321
B-1-48-10-H-DS	Grade 8	3/4	335	Yes	0.071	2.625	10.0	3.50	10.563	52.43	69.28	1.321

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-0-49-1-0-DS	Grade 8	1/2	0	No	0.071	1.781	6.70	3.56	7.042	52.43	69.28	1.321
B-0-49-2-0-DS	Grade 8	1/2	0	No	0.071	1.813	6.70	3.63	7.042	52.43	69.28	1.321
B-0-49-3-L-DS	Grade 8	1/2	40	No	0.071	1.781	6.70	3.56	7.042	52.43	69.28	1.321
B-0-49-4-L-DS	Grade 8	1/2	40	No	0.071	1.781	6.70	3.56	7.042	52.43	69.28	1.321
B-0-49-5-H-DS	Grade 8	1/2	95	No	0.071	1.781	6.70	3.56	7.042	52.43	69.28	1.321
B-0-49-6-H-DS	Grade 8	1/2	95	No	0.071	1.781	6.70	3.56	7.042	52.43	69.28	1.321
B-0-50-1-0-DS	A307	3/4	0	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-2-0-DS	A307	3/4	0	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-3-L-DS	A307	3/4	110	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-4-L-DS	A307	3/4	110	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-5-0-DS	Grade 8	3/4	0	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-6-0-DS	Grade 8	3/4	0	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-7-L-DS	Grade 8	3/4	110	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-8-L-DS	Grade 8	3/4	110	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-9-H-DS	Grade 8	3/4	335	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-50-10-H-DS	Grade 8	3/4	335	No	0.071	2.625	10.00	3.50	10.563	52.43	69.28	1.321
B-0-51-1-0-SS	Grade 8	3/4	0	No	0.184	1.688	4.25	2.25	4.076	54.16	70.69	1.305
B-0-51-2-0-SS	Grade 8	3/4	0	No	0.184	1.688	4.25	2.25	4.076	54.16	70.69	1.305
B-0-51-3-L-SS	Grade 8	3/4	110	No	0.184	1.719	4.25	2.29	4.076	54.16	70.69	1.305
B-0-51-4-L-SS	Grade 8	3/4	110	No	0.184	1.688	4.25	2.25	4.076	54.16	70.69	1.305
B-0-51-5-H-SS	Grade 8	3/4	335	No	0.184	1.688	4.25	2.25	4.076	54.16	70.69	1.305
B-0-51-6-H-SS	Grade 8	3/4	335	No	0.184	1.688	4.25	2.25	4.076	54.16	70.69	1.305

Table 3a

Dimensions and Mechanical Properties of Bolted Connection Specimens
(Continued)

Spec. No.	Grade of bolt	d (in.)	Torque (ft-lb)	Washers	t (in.)	e (in.)	s (in.)	e/d	d/t	F_y (ksi)	F_u (ksi)	F_u/F_y
B-1-52-1-0-DS	Grade 8	3/4	0	Yes	0.184	2.594	10.00	3.46	4.076	54.16	70.69	1.305
B-1-52-2-0-DS	Grade 8	3/4	0	Yes	0.184	2.594	10.00	3.46	4.076	54.16	70.69	1.305
B-1-52-3-L-DS	Grade 8	3/4	110	Yes	0.184	2.625	10.00	3.50	4.076	54.16	70.69	1.305
B-1-52-4-L-DS	Grade 8	3/4	110	Yes	0.184	2.625	10.00	3.50	4.076	54.16	70.69	1.305
B-1-52-5-H-DS	Grade 8	3/4	335	Yes	0.184	2.563	10.00	3.42	4.076	54.16	70.69	1.305
B-0-53-1-0-DS	Grade 8	3/4	0	No	0.184	2.625	10.00	3.50	4.076	54.16	70.69	1.305
B-0-53-2-0-DS	Grade 8	3/4	0	No	0.184	2.688	10.00	3.58	4.076	54.16	70.69	1.305
B-0-53-3-L-DS	Grade 8	3/4	110	No	0.184	2.625	10.00	3.50	4.076	54.16	70.69	1.305
B-0-53-4-L-DS	Grade 8	3/4	110	No	0.184	2.656	10.00	3.54	4.076	54.16	70.69	1.305
B-0-53-5-H-DS	Grade 8	3/4	335	No	0.184	2.563	10.00	3.42	4.076	54.16	70.69	1.305

Notes: 1. See Figs 1 for the definition of symbols used in this table.
2. The specimens are designated as follows:

B - 1 - 11 - 1 - 0 - SS

- Type of shear connection:
  - SS - single shear
  - DS - double shear
- Type of torque:
  - 0 - no torque
  - L - low torque (Table 1a)
  - H - high torque (Table 1b)
- Test No.
- No. of specimen
- Washers used:
  - 0 - without washers
  - 1 - with washers
- Bearing test

Table 3b

Dimensions of Bolts

Diameter of Bolt (In.)	Type of Bolt	L (In.)	C (In.)	H (In.)
1/4	A307	1.00	0.438	0.125
1/4	Grade 8	1.00	0.438	0.125
1/2	A307	1.00	0.750	0.313
1/2	Grade 8	1.25	0.750	0.313
3/4	A307	1.00	1.125	0.438
3/4	Grade 8	1.25	1.094	0.438

Supplied by Bosco Fastening Service Center, Kansas City, Mo.

Table 3c

Dimensions of Nuts

Diameter of Bolt (In.)	Type of Bolt	F (In.)	N (In.)
1/4	A307	0.438	0.219
1/4	Grade 8	0.438	0.219
1/2	A307	0.750	0.438
1/2	Grade 8	0.750	0.438
3/4	A307	1.125	0.625
3/4	Grade 8	1.094	0.625

Supplied by Bosco Fastening Service Center, Kansas City, Mo.

Table 3d

Dimensions of Washers

Diameter of Bolt (In.)	Type of Bolt	Outer Diameter (In.)	Inner Diameter (In.)
1/4	A307	0.750	0.313
1/4	Grade 8	0.750	0.313
1/2	A307	1.375	0.563
1/2	Grade 8	1.125	0.563
3/4	A307	2.000	0.813
3/4	Grade 8	1.469	0.844

Supplied by Bosco Fastening Service Center, Kansas City, Mo.

Table 4

Test Results of Bolted Connections

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-1-11-1-0-SS	0.420	120.00	II & I
B-1-11-2-0-SS	0.417	119.14	II & I
B-1-11-3-L-SS	0.513	146.57	II & I
B-1-11-4-L-SS	0.577	164.86	II & I
B-1-11-5-0-SS	0.430	122.86	II & I
B-1-11-6-0-SS	0.400	114.29	II & I
B-1-11-7-L-SS	0.597	170.57	II & I
B-1-11-8-L-SS	0.530	151.43	II & I
B-1-11-9-H-SS	0.727	207.71	II & I
B-1-11-10-H-SS	0.642	183.43	II & I
B-0-12-1-0-SS	0.388	110.86	V
B-0-12-2-0-SS	0.315	90.00	V
B-0-12-3-L-SS	0.315	90.00	V
B-0-12-4-L-SS	0.338	96.57	V
B-0-12-5-0-SS	0.305	87.14	V
B-0-12-6-0-SS	0.323	92.29	V
B-0-12-7-L-SS	0.356	101.71	V
B-0-12-8-L-SS	0.326	93.14	V
B-0-12-9-H-SS	0.383	109.43	V
B-0-12-10-H-SS	0.505	144.29	V
B-1-13-1-0-DS	0.506	144.57	II & I
B-1-13-2-0-DS	0.507	144.86	II & I
B-1-13-3-L-DS	0.811	231.71	II & I
B-1-13-4-L-DS	0.744	212.57	II & I
B-1-13-5-0-DS	0.576	164.57	II & I
B-1-13-6-0-DS	0.482	137.71	II & I
B-1-13-7-L-DS	0.780	222.86	II & I
B-1-13-8-L-DS	0.795	227.14	II & I
B-1-13-9-H-DS	0.806	230.29	II & I
B-1-13-10-H-DS	0.855	244.29	II & I
B-0-14-1-0-DS	0.543	155.14	II & I
B-0-14-2-0-DS	0.478	136.57	II & I
B-0-14-3-L-DS	0.574	164.00	II & I
B-0-14-4-L-DS	0.530	151.43	II & I
B-0-14-5-0-DS	0.523	149.43	II & I
B-0-14-6-0-DS	0.482	137.71	II & I
B-0-14-7-L-DS	0.688	196.57	II & I
B-0-14-8-L-DS	0.708	202.29	II & I
B-0-14-9-H-DS	0.552	157.71	II & I
B-0-14-10-H-DS	0.542	154.86	II & I

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-1-15-1-0-SS	1.552	172.44	II & I
B-1-15-2-0-SS	1.553	172.56	II & I
B-1-15-3-L-SS	1.790	198.89	II & I
B-1-15-4-L-SS	1.670	185.56	II & I
B-1-15-5-H-SS	1.828	203.11	II & I
B-1-15-6-H-SS	1.847	205.22	II & I
B-1-16-1-0-SS	3.37	187.22	II & III
B-1-16-2-0-SS	3.21	178.33	II & III
B-1-16-3-L-SS	2.64	146.67	II & III
B-1-16-4-L-SS	2.795	155.28	II & III
B-1-16-5-0-SS	1.95	108.33	II & V
B-1-16-6-0-SS	2.00	111.11	II & V
B-1-16-7-L-SS	2.08	115.56	II & V
B-1-16-8-L-SS	2.35	130.56	II & V
B-1-16-9-H-SS	2.58	143.33	II & V
B-1-16-10-H-SS	2.95	163.89	II & V
B-0-17-1-0-SS	1.217	135.22	V
B-0-17-2-0-SS	1.115	123.89	V
B-0-17-3-L-SS	1.204	133.78	V
B-0-17-4-L-SS	1.292	143.56	V
B-0-17-5-0-SS	1.187	131.89	V
B-0-17-6-0-SS	1.194	132.67	V
B-0-17-7-L-SS	1.195	132.78	V
B-0-17-8-L-SS	1.225	136.11	V
B-0-17-9-H-SS	1.198	133.11	V
B-0-17-10-H-SS	1.214	134.89	V
B-0-18-1-0-SS	1.415	78.61	V
B-0-18-2-0-SS	1.420	78.89	V
B-0-18-3-L-SS	2.040	113.33	V
B-0-18-4-L-SS	1.490	82.78	V
B-0-18-5-0-SS	1.420	78.88	V
B-0-18-6-0-SS	1.596	88.67	V
B-0-18-7-L-SS	2.735	151.94	V
B-0-18-8-L-SS	2.580	143.33	V
B-0-18-9-H-SS	2.610	145.00	V
B-0-18-10-H-SS	2.340	130.00	V

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-1-19-1-0-DS	1.915	212.78	II & I
B-1-19-2-0-DS	1.820	202.22	II & I
B-1-19-3-L-DS	2.120	235.56	II & I
B-1-19-4-L-DS	2.090	232.22	II & I
B-1-19-5-0-DS	1.960	217.78	II & I
B-1-19-6-0-DS	1.550	172.22	II & I
B-1-19-7-L-DS	1.975	219.44	II & I
B-1-19-8-L-DS	2.170	241.11	II & I
B-1-19-9-H-DS	2.435	270.56	II & I
B-1-19-10-H-DS	2.325	258.33	II & I
B-1-20-1-0-DS	3.035	168.61	II & I
B-1-20-2-0-DS	2.940	163.33	II & I
B-1-20-3-L-DS	3.860	214.44	II & I
B-1-20-4-L-DS	3.735	207.50	II & I
B-1-20-5-0-DS	2.890	160.56	II & I
B-1-20-6-0-DS	3.380	187.78	II & I
B-1-20-8-L-DS	4.110	228.33	II & I
B-1-20-9-H-DS	4.415	245.28	II & I
B-1-20-10-H-DS	4.465	248.06	II & I
B-0-21-1-0-DS	1.880	208.89	II & I
B-0-21-2-0-DS	1.900	211.11	II & I
B-0-21-3-L-DS	1.900	211.11	II & I
B-0-21-4-L-DS	1.915	212.78	II & I
B-0-21-5-0-DS	1.940	215.56	II & I
B-0-21-6-0-DS	2.030	225.56	II & I
B-0-21-7-L-DS	2.175	241.67	II & I
B-0-21-8-L-DS	2.050	227.78	II & I
B-0-21-9-H-DS	2.235	248.33	II & I
B-0-21-10-H-DS	2.000	222.22	II & I
B-0-22-1-0-DS	2.560	146.22	II & I
B-0-22-2-0-DS	2.485	138.06	II & I
B-0-22-3-L-DS	2.875	159.72	II & I
B-0-22-4-L-DS	2.425	134.72	II & I
B-0-22-5-0-DS	2.425	134.72	II & V
B-0-22-6-0-DS	2.200	122.22	II & V
B-0-22-7-L-DS	2.700	150.00	II & I
B-0-22-8-L-DS	2.720	151.11	II & I
B-0-22-9-H-DS	2.650	147.22	II & I
B-0-22-10-H-DS	2.860	158.89	II & I

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-1-23-1-0-SS	6.625	179.10	V
B-1-23-2-0-SS	7.440	201.10	V
B-1-23-3-L-SS	7.450	201.35	V
B-1-23-4-L-SS	7.740	209.19	V
B-1-23-5-H-SS	7.970	215.41	V
B-1-23-6-H-SS	7.815	211.22	V
B-1-24-1-0-SS	9.000	162.16	II & I
B-1-24-2-0-SS	9.275	167.12	II & I
B-1-24-3-L-SS	10.700	192.80	II & V
B-1-24-4-L-SS	10.750	193.70	II & I
B-1-24-5-0-SS	7.200	129.73	II & III
B-1-24-6-0-SS	7.150	128.83	II & III
B-1-24-7-L-SS	7.550	136.04	II & III
B-1-24-8-L-SS	6.800	122.52	II & III
B-1-24-9-H-SS	8.700	156.76	II & III
B-1-24-10-H-SS	8.000	144.14	II & III
B-0-25-1-0-SS	4.09	110.54	V
B-0-25-2-0-SS	4.27	115.41	V
B-0-25-3-L-SS	4.54	122.70	V
B-0-25-4-L-SS	4.73	127.84	V
B-0-25-5-H-SS	4.59	124.05	V
B-0-25-6-H-SS	4.35	117.57	V
B-0-26-1-0-SS	5.480	98.74	V
B-0-26-2-0-SS	5.555	100.10	V
B-0-26-3-L-SS	5.690	102.52	V
B-0-26-4-L-SS	5.540	99.82	V
B-0-26-5-0-SS	5.550	100.00	V
B-0-26-6-0-SS	5.180	93.33	V
B-0-26-7-L-SS	5.620	101.26	V
B-0-26-8-L-SS	5.600	100.90	V
B-0-26-9-H-SS	7.000	126.13	V
B-0-26-10-H-SS	7.350	132.43	V
B-1-27-1-0-DS	7.275	196.62	II & I
B-1-27-2-0-DS	7.480	202.16	II & I
B-1-27-3-L-DS	10.550	285.14	II & I
B-1-27-4-L-DS	10.250	277.03	II & I
B-1-27-5-0-DS	7.200	194.59	II & I
B-1-27-6-0-DS	7.625	206.08	II & I
B-1-27-7-L-DS	10.750	290.54	II & I
B-1-27-8-L-DS	9.750	263.51	II & I
B-1-27-9-H-DS	10.350	279.73	II & I
B-1-27-10-H-DS	9.650	260.81	II & I

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	$(P_u)_{test}$ (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type
B-1-28-1-0-DS	10.850	195.50	II & I
B-1-28-2-0-DS	13.300	239.64	II & I
B-1-26-3-L-DS	13.450	242.34	II & I
B-1-28-4-L-DS	14.300	257.66	II & I
B-1-28-5-0-DS	10.750	193.70	II & I
B-1-28-6-0-DS	11.950	215.32	II & I
B-1-28-7-L-DS	13.850	249.55	II & I
B-1-28-8-L-DS	12.950	233.33	II & I
B-1-28-9-H-DS	15.700	282.88	II & I
B-1-28-10-H-DS	13.650	245.95	II & I
B-0-29-1-0-DS	6.935	187.43	II & I
B-0-29-2-0-DS	7.990	215.95	II & I
B-0-29-3-L-DS	8.600	232.43	II & I
B-0-29-4-L-DS	8.650	233.78	II & I
B-0-29-5-0-DS	8.315	224.73	II & I
B-0-29-6-0-DS	7.060	190.81	II & I
B-0-29-7-L-DS	9.200	248.65	II & I
B-0-29-8-L-DS	9.300	251.35	II & I
B-0-29-9-H-DS	9.250	250.00	II & I
B-0-29-10-H-DS	9.150	247.30	II & I
B-0-30-1-0-DS	9.950	179.28	II & I
B-0-30-2-0-DS	10.500	189.20	II & I
B-0-30-3-L-DS	11.500	207.21	II & I
B-0-30-4-L-DS	10.800	194.60	II & I
B-0-30-5-0-DS	10.375	186.94	II & I
B-0-30-6-0-DS	9.830	177.12	II & I
B-0-30-7-L-DS	11.120	200.36	II & I
B-0-30-8-L-DS	10.820	194.95	II & I
B-0-30-9-H-DS	11.300	203.60	II & I
B-0-30-10-H-DS	11.600	209.01	II & I
B-1-31-1-0-SS	0.734	190.65	II & III
B-1-31-2-0-SS	0.694	180.26	II & III
B-1-31-3-L-SS	0.896	232.73	II & III
B-1-31-4-L-SS	0.882	229.10	II & III
B-1-31-5-0-SS	0.628	163.12	II & III
B-1-31-6-0-SS	0.748	194.29	II & III
B-1-31-7-L-SS	0.907	235.58	II & III
B-1-31-8-L-SS	0.753	195.58	II & III
B-1-31-9-H-SS	1.083	281.30	II & III
B-1-31-10-H-SS	0.914	237.40	II & III

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-0-32-1-0-SS	0.550	142.86	II & V
B-0-32-2-0-SS	0.580	150.65	II & V
B-0-32-3-L-SS	0.612	158.96	II & V
B-0-32-4-L-SS	0.706	183.38	II & V
B-0-32-5-0-SS	0.600	155.84	II & V
B-0-32-6-0-SS	0.542	140.78	II & V
B-0-32-7-L-SS	0.560	145.45	II & V
B-0-32-8-L-SS	0.537	139.48	II & V
B-0-32-9-H-SS	0.812	210.91	II & III
B-0-32-10-H-SS	0.650	168.83	II & III
B-1-33-1-0-DS	0.700	181.82	II & I
B-1-33-2-0-DS	0.698	181.30	II & I
B-1-33-3-L-DS	0.895	232.47	II & I
B-1-33-4-L-DS	1.022	265.45	II & I
B-1-33-5-0-DS	0.788	204.68	II & I
B-1-33-6-0-DS	0.668	173.51	II & I
B-1-33-7-L-DS	1.105	287.01	II & I
B-1-33-8-L-DS	1.109	288.05	II & I
B-1-33-9-H-DS	1.231	319.74	II & I
B-1-33-10-H-DS	1.158	300.78	II & I
B-0-34-1-0-DS	0.850	220.78	II & I
B-0-34-2-0-DS	0.857	222.60	II & I
B-0-34-3-L-DS	0.956	248.31	II & I
B-0-34-4-L-DS	0.996	258.70	II & I
B-0-34-5-0-DS	0.690	179.22	II & I
B-0-34-6-0-DS	0.815	211.69	II & I
B-0-34-7-L-DS	0.870	225.97	II & I
B-0-34-8-L-DS	1.038	269.61	II & I
B-0-34-9-H-DS	1.130	263.51	II & I
B-0-34-10-H-DS	0.907	235.58	II & I
B-1-35-1-0-SS	1.884	243.10	II & I
B-1-35-2-0-SS	2.000	258.06	II & I
B-1-35-3-L-SS	2.050	264.52	II & I
B-1-35-4-L-SS	1.830	236.13	II & I
B-1-35-5-H-SS	2.070	267.10	II & I
B-1-35-6-H-SS	2.030	261.94	II & I

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	$(P_u)_{test}$ (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type
B-0-46-1-0-SS	5.825	109.39	II & V
B-0-46-2-0-SS	5.470	102.72	II & V
B-0-46-3-L-SS	6.000	112.68	II & V
B-0-46-4-L-SS	5.960	111.92	II & V
B-0-46-5-0-SS	5.870	110.23	II & V
B-0-46-6-0-SS	5.820	109.30	II & V
B-0-46-7-L-SS	6.690	125.63	II & V
B-0-46-8-L-SS	5.875	110.33	II & V
B-0-46-9-H-SS	7.500	140.85	II & V
B-0-46-10-H-SS	6.560	123.19	II & V
B-1-47-1-0-DS	10.100	284.51	II & I
B-1-47-2-0-DS	9.995	281.55	II & I
B-1-47-3-L-DS	10.100	284.51	II & I
B-1-47-4-L-DS	10.575	297.89	II & I
B-1-47-5-H-DS	11.425	321.83	II & I
B-1-48-1-0-DS	11.750	220.66	II & I
B-1-48-2-0-DS	12.350	231.92	II & I
B-1-48-3-L-DS	14.675	275.59	II & I
B-1-48-4-L-DS	14.250	267.61	II & I
B-1-48-5-0-DS	12.450	233.80	II & I
B-1-48-6-0-DS	13.150	246.95	II & I
B-1-48-7-L-DS	12.920	242.63	II & I
B-1-48-8-L-DS	13.850	260.09	II&& I
B-1-48-9-H-DS	15.675	294.37	II & I
B-1-48-10-H-DS	13.500	253.52	II & I
B-0-49-1-0-DS	9.575	269.72	II & I
B-0-49-2-0-DS	8.400	236.62	II & I
B-0-49-3-L-DS	8.820	248.45	II & I
B-0-49-4-L-DS	8.950	252.11	II & I
B-0-49-5-H-DS	9.200	259.15	II & I
B-0-49-6-H-DS	9.500	267.61	II & I
B-0-50-1-0-DS	12.25	230.05	II & I
B-0-50-2-0-DS	11.90	223.47	II & I
B-0-50-3-L-DS	12.45	233.80	II & I
B-0-50-4-L-DS	11.65	218.78	II & I
B-0-50-5-0-DS	11.35	213.15	II & I
B-0-50-6-0-DS	10.85	203.76	II & I
B-0-50-7-L-DS	12.00	225.35	II & I
B-0-50-8-L-DS	10.08	189.30	II & I
B-0-50-9-H-DS	14.00	262.91	II & I
B-0-50-10-H-DS	12.025	263.38	II & I

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-0-41-1-0-DS	1.980	255.48	II & I
B-0-41-3-0-DS	2.165	279.35	II & I
B-0-41-3-L-DS	2.390	308.39	II & I
B-0-41-4-L-DS	2.130	274.84	II & I
B-0-41-5-H-DS	2.320	299.35	II & I
B-0-41-6-H-DS	2.400	309.68	II & I
B-0-42-1-0-DS	2.945	190.60	II & I
B-0-42-2-0-DS	2.710	174.84	II & I
B-0-42-3-L-DS	2.880	185.81	II & I
B-0-42-4-L-DS	2.730	176.13	II & I
B-0-42-5-0-DS	3.010	194.19	II & I
B-0-42-6-0-DS	3.010	194.19	II & I
B-0-42-7-L-DS	3.780	243.87	II & I
B-0-42-8-L-DS	2.850	183.87	II & I
B-0-42-9-H-DS	3.875	250.00	II & I
B-0-42-10-H-DS	4.340	280.00	II & I
B-1-43-1-0-SS	6.575	185.21	II & III
B-1-43-2-0-SS	6.910	194.65	II & V
B-1-43-3-L-SS	8.130	229.01	II & V
B-1-43-4-L-SS	7.12	200.56	II & V
B-1-43-5-H-SS	6.89	194.08	II & V
B-1-43-6-H-SS	6.83	192.39	II & V
B-1-44-1-0-SS	11.100	208.45	II & I
B-1-44-3-L-SS	12.200	229.11	II & I
B-1-44-4-L-SS	11.550	216.90	II & III
B-1-44-5-0-SS	8.250	154.93	II & III
B-1-44-6-0-SS	8.150	153.05	II & V
B-1-44-7-L-SS	8.000	150.23	II & V
B-1-44-8-L-SS	8.150	153.05	II & III
8-1-44-9-H-SS	8.500	159.62	II & III
B-1-44-10-H-SS	8.250	154.93	II & V
B-0-45-1-0-SS	4.040	113.80	V
B-0-45-2-0-SS	4.080	114.93	V
B-0-45-3-L-SS	4.335	122.11	V
B-0-45-4-L-SS	4.325	121.83	V
B-0-45-5-H-SS	4.460	125.63	V
B-0-45-6-H-SS	4.450	125.35	V

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	$(P_u)_{test}$ (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type
B-1-36-1-0-SS	2.600	167.74	II & III
B-1-36-2-0-SS	2.490	160.65	II & III
B-1-36-3-L-SS	2.940	189.68	II & III
B-1-36-4-L-SS	2.960	190.97	II & III
B-1-36-5-0-SS	2.370	152.90	II & III
B-1-36-6-0-SS	2.290	147.74	II & III
B-1-36-7-L-SS	2.460	158.71	II & III
B-1-36-8-L-SS	2.360	152.26	II & III
B-1-36-9-H-SS	3.110	200.65	II & V
B-1-36-10-H-SS	3.320	214.19	II & III
B-0-37-1-0-SS	1.207	155.74	V
B-0-37-2-0-SS	1.204	155.35	V
B-0-37-3-L-SS	1.262	162.84	V
B-0-37-4-L-SS	1.248	161.03	V
B-0-37-5-H-SS	1.241	160.13	V
B-0-37-6-H-SS	1.995	154.19	V
B-0-38-1-0-SS	1.575	101.61	V
B-0-38-2-0-SS	1.635	105.48	V
B-0-38-3-L-SS	2.260	145.81	V
B-0-38-4-L-SS	1.950	125.81	V
B-0-38-5-0-SS	1.615	104.19	V
B-0-38-6-0-SS	1.675	108.06	V
B-0-38-7-L-SS	2.345	151.29	V
B-0-38-8-L-SS	1.840	118.71	V
B-0-38-9-H-SS	2.100	135.48	V
B-0-38-10-H-SS	2.330	150.32	V
B-1-39-1-0-DS	1.700	219.35	II & I
B-1-39-2-0-DS	1.750	225.81	II & I
B-1-39-3-L-DS	2.500	322.58	II & I
B-1-39-4-L-DS	2.485	320.65	II & I
B-1-39-5-H-DS	2.410	310.97	II & I
B-1-40-1-0-DS	2.755	177.74	II & I
B-1-40-2-0-DS	2.830	182.58	II & I
B-1-40-3-L-DS	4.065	262.26	II & I
B-1-40-4-L-DS	3.950	254.84	II & I
B-1-40-5-0-DS	2.800	180.65	II & I
B-1-40-6-0-DS	2.830	182.58	II & I
B-1-40-7-L-DS	4.085	263.55	II & I
B-1-40-8-L-DS	4.035	260.32	II & I
B-1-40-9-H-DS	4.475	288.71	II & I
B-1-40-10-H-DS	4.630	298.71	II & I

Table 4

Test Results of Bolted Connections
(Continued)

Spec. No.	(P_u) test (kips)	(σ_b) test (ksi)	Failure Type
B-0-51-1-0-SS	21.950	159.06	V
B-0-51-2-0-SS	21.650	156.88	V
B-0-51-3-L-SS	21.150	153.26	V
B-0-51-4-L-SS	22.900	165.94	V
B-0-51-5-H-SS	21.350	154.71	V
B-0-51-6-H-SS	22.000	159.42	V
B-1-52-1-0-DS	34.75	251.81	II & I
B-1-52-2-0-DS	35.80	259.42	II & I
B-1-52-3-L-DS	36.85	267.03	II & I
B-1-52-4-L-DS	36.50	264.49	II & I
B-1-52-5-H-DS	35.80	259.42	II & I
B-0-53-1-0-DS	35.50	257.25	II & I
B-0-53-2-0-DS	34.90	252.90	II & I
B-0-53-3-L-DS	36.40	263.77	II & I
B-0-53-4-L-DS	36.15	261.96	II & I
B-0-53-5-H-DS	36.10	261.59	II & I

Notes: The failure types are defined as follows:

- I - longitudinal shearing of the steel sheets
- II - bearing failure between steel sheet and bolt
- III - transverse tension tearing failure of steel sheet
- IV - shearing of the bolt
- V - tearing of sheet caused by the excessive bolt rotation and warping of steel sheet

Table 5a

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Single Shear With Washers

Zero Torque

0.024" $\leq t <$ 3/16"

Specimen No.	Type of Bolt	d/t	$(P_u)_{test}$ (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-1-15-1-0-SS	Gr. 8	6.94	1.552	172.44	II & I	65.95	2.61
B-1-15-2-0-SS	"	6.94	1.558	172.56	II & I	65.95	2.61
B-1-16-1-0-SS	A307	13.89	3.37	187.22	II & III	65.95	2.84
B-1-16-2-0-SS	"	13.89	3.21	178.33	II & III	65.95	2.70
B-1-16-5-0-SS	Gr. 8	13.89	1.95	108.33	V	65.95	1.64
B-1-16-6-0-SS	"	13.89	2.00	111.11	V	65.95	1.68
B-1-23-1-0-SS	Gr. 8	6.76	6.625	179.10	V	72.50	2.47
B-1-23-2-0-SS	"	6.76	7.440	201.10	V	72.50	2.77
B-1-24-1-0-SS	A307	10.14	9.000	162.16	II & I	72.50	2.24
B-1-24-2-0-SS	"	10.14	9.275	167.12	II & I	72.50	2.31
B-1-24-5-0-SS	Gr. 8	10.14	7.20	129.73	II & III	72.50	1.79
B-1-24-6-0-SS	"	10.14	7.15	128.83	II & III	72.50	1.78
B-1-35-1-0-SS	Gr. 8	8.07	1.884	243.10	II & I	100.59	2.42
B-1-35-2-0-SS	"	8.07	2.000	258.06	II & I	100.59	2.57
B-1-36-1-0-SS	A307	16.13	2.600	167.74	II & III	100.59	1.67
B-1-36-2-0-SS	"	16.13	2.490	160.65	II & III	100.59	1.60
B-1-36-5-0-SS	Gr. 8	16.13	2.390	152.90	II & III	100.59	1.52
B-1-36-6-0-SS	"	16.13	2.290	147.74	II & III	100.59	1.47
B-1-43-1-0-SS	Gr. 8	7.04	6.575	185.21	II & III	93.53	1.98
B-1-43-2-0-SS	"	7.04	6.910	194.65	II & V	93.53	2.08
B-1-44-1-0-SS	A307	10.56	11.100	208.45	II & I	93.53	2.23
B-1-44-5-0-SS	Gr. 8	10.56	8.250	154.93	II & III	93.53	1.66
B-1-44-6-0-SS	"	10.56	8.150	153.05	II & V	93.53	1.64
Mean Value							2.10
Standard Deviation							0.457
Coefficient of Variation							0.218

Table 5b

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Single Shear With Washers

Low Torque

0.024" $\leq$ t < 3/16"

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-1-15-3-L-SS	Gr. 8	6.94	1.79	198.89	II & I	65.95	3.02
B-1-15-4-L-SS	"	6.94	1.67	185.56	II & I	65.95	2.81
B-1-16-3-L-SS	A307	13.89	2.64	146.67	II & III	65.95	2.22
B-1-16-4-L-SS	"	13.89	2.795	155.28	II & III	65.95	2.35
B-1-16-7-L-SS	Gr. 8	13.89	2.08	115.56	II & V	65.95	1.75
B-1-16-8-L-SS	"	13.89	2.35	130.56	II & V	65.95	1.98
B-1-23-3-L-SS	Gr. 8	6.76	7.45	201.35	V	72.50	2.78
B-1-23-4-L-SS	"	6.76	7.74	209.19	V	72.50	2.89
B-1-24-3-L-SS	A307	10.14	10.70	192.80	II & V	72.50	2.66
B-1-24-4-L-SS	"	10.14	10.75	193.70	II & V	72.50	2.67
B-1-24-7-L-SS	Gr. 8	10.14	7.55	136.04	II & III	72.50	1.88
B-1-24-8-L-SS	"	10.14	6.80	122.52	II & III	72.50	1.69
B-1-35-3-L-SS	Gr. 8	8.07	2.05	264.52	II & I	100.59	2.63
B-1-35-4-L-SS	"	8.07	1.83	236.13	II & I	100.59	2.35
B-1-36-3-L-SS	A307	16.13	2.94	189.68	II & III	100.59	1.89
B-1-36-4-L-SS	"	16.13	2.96	180.97	II & III	100.59	1.90
B-1-36-7-L-SS	Gr. 8	16.13	2.46	158.71	II & III	100.59	1.58
B-1-36-8-L-SS	"	16.13	2.36	152.26	II & III	100.59	1.51
B-1-43-3-L-SS	Gr. 8	7.04	8.13	229.01	II & V	93.53	2.45
B-1-43-4-L-SS	"	7.04	7.12	200.56	II & V	93.53	2.14
B-1-44-3-L-SS	A307	10.56	12.20	229.11	II & I	93.53	2.45
B-1-44-4-L-SS	"	10.56	11.55	216.90	II & III	93.53	2.32
B-1-44-7-L-SS	Gr. 8	10.56	8.00	150.23	II & V	93.53	1.61
B-1-44-8-L-SS	"	10.56	8.15	153.05	II & III	93.53	1.64
Mean Value							2.22
Standard Deviation							0.465
Coefficient of Variation							0.233

Table 5c

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Single Shear With Washers

High Torque

$0.024'' \leq t < 3/16''$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-1-15-5-H-SS	Gr. 8	6.94	1.828	208.11	II & I	65.95	3.08
B-1-15-6-H-SS	"	6.94	1.847	205.22	II & I	65.95	3.11
B-1-16-9-H-SS	Gr. 8	13.89	2.58	143.33	II & V	65.95	2.17
B-1-16-10-H-SS	"	13.89	2.95	163.89	II & V	65.95	2.49
B-1-23-5-H-SS	Gr. 8	6.76	7.97	215.41	V	72.50	2.97
B-1-23-6-H-SS	"	6.76	7.815	211.22	V	72.50	2.91
B-1-24-9-H-SS	Gr. 8	10.14	8.70	156.76	II & III	72.50	2.16
B-1-24-10-H-SS	"	10.14	8.00	144.14	II & III	72.50	1.99
B-1-35-5-H-SS	Gr. 8	8.07	2.07	267.10	II & I	100.59	2.66
B-1-35-6-H-SS	"	8.07	2.03	261.94	II & I	100.59	2.60
B-1-36-9-H-SS	Gr. 8	16.13	3.11	200.65	II & V	100.59	1.99
B-1-36-10-H-SS	"	16.13	3.32	214.19	II & III	100.59	2.13
B-1-43-5-H-SS	Gr. 8	7.04	6.89	194.08	II & V	93.53	2.08
B-1-43-6-H-SS	"	7.04	6.83	192.39	II & V	93.53	2.06
B-1-44-9-H-SS	Gr. 8	10.56	8.50	159.62	II & III	93.53	1.71
B-1-44-10-H-SS	"	10.56	8.25	154.93	II & V	93.53	1.66
Mean Value							2.36
Standard Deviation							0.476
Coefficient of Variation							0.202

Table 6a

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Double Shear With Washers

Zero Torque

$0.024" \leq t < 3/16"$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-1-19-1-0-DS	A307	6.94	1.915	212.78	II & I	73.28	2.90
B-1-19-2-0-DS	"	6.94	1.820	202.22	II & I	73.28	2.76
B-1-19-5-0-DS	Gr. 8	6.94	1.96	217.78	II & I	73.28	2.97
B-1-19-6-0-DS	"	6.94	1.55	172.22	II & I	73.28	2.35
B-1-20-1-0-DS	A307	13.89	3.035	168.61	II & I	73.28	2.30
B-1-20-2-0-DS	"	13.89	2.940	163.33	II & I	73.28	2.23
B-1-20-5-0-DS	Gr. 8	13.89	2.89	160.56	II & I	73.28	2.19
B-1-20-6-0-DS	"	13.89	3.38	187.78	II & I	73.28	2.56
B-1-27-1-0-DS	A307	6.76	7.275	196.62	II & I	72.50	2.71
B-1-27-2-0-DS	"	6.76	7.480	202.16	II & I	72.50	2.79
B-1-27-5-0-DS	Gr. 8	6.76	7.20	194.59	II & I	72.50	2.68
B-1-27-6-0-DS	"	6.76	7.625	206.08	II & I	72.50	2.84
B-1-28-1-0-DS	A307	10.14	10.85	195.50	II & I	72.50	2.70
B-1-28-2-0-DS	"	10.14	13.30	239.64	II & I	72.50	3.31
B-1-28-5-0-DS	Gr. 8	10.14	10.75	193.70	II & I	72.50	2.67
B-1-28-6-0-DS	"	10.14	11.95	215.32	II & I	72.50	2.97
B-1-39-1-0-DS	Gr. 8	8.07	1.70	219.35	II & I	111.77	1.96
B-1-39-2-0-DS	"	8.07	1.75	225.81	II & I	111.77	2.02
B-1-40-1-0-DS	A307	16.13	2.755	177.74	II & I	111.77	1.59
B-1-40-2-0-DS	"	16.13	2.830	182.58	II & I	111.77	1.63
B-1-40-5-0-DS	Gr. 8	16.13	2.800	180.65	II & I	111.77	1.62
B-1-40-6-0-DS	"	16.13	2.830	182.58	II & I	111.77	1.63
B-1-47-1-0-DS	Gr. 8	7.04	10.10	284.51	II & I	103.92	2.74
B-1-47-2-0-DS	"	7.04	9.995	281.55	II & I	103.92	2.71
B-1-28-1-0-DS	A307	10.56	11.75	220.66	II & I	103.92	2.12
B-1-48-2-0-DS	"	10.56	12.35	231.92	II & I	103.92	2.23
B-1-48-5-0-DS	Gr. 8	10.56	12.45	233.80	II & I	103.92	2.25
B-1-48-6-0-DS	"	10.56	13.15	246.95	II & I	103.92	2.38
Mean Value							2.42
Standard Deviation							0.462
Coefficient of Variation							0.191

Table 6b

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Double Shear With Washers

Low Torque

$0.024'' \leq t < 3/16''$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-1-19-3-L-DS	A307	6.94	2.12	235.56	II & I	73.28	3.21
B-1-19-4-L-DS	"	6.94	2.09	232.22	II & I	73.28	3.17
B-1-19-7-L-DS	Gr. 8	6.94	1.975	219.44	II & I	73.28	2.99
B-1-19-8-L-DS	"	6.94	2.170	241.11	II & I	73.28	3.29
B-1-20-3-L-DS	A307	13.89	3.860	214.44	II & I	73.28	2.93
B-1-20-4-L-DS	"	13.89	3.735	207.50	II & I	73.28	2.83
B-1-20-8-L-DS	Gr. 8	13.89	4.110	228.33	II & I	73.28	3.12
B-1-27-3-L-DS	A307	6.76	10.550	285.14	II & I	72.50	3.93
B-1-27-4-L-DS	"	6.76	10.250	277.03	II & I	72.50	3.82
B-1-27-7-L-DS	Gr. 8	6.76	10.750	290.54	II & I	72.50	4.01
B-1-27-8-L-DS	"	6.76	9.750	263.51	II & I	72.50	3.63
B-1-28-3-L-DS	A307	10.14	13.450	242.34	II & I	72.50	3.34
B-1-28-4-L-DS	"	10.14	14.300	257.66	II & I	72.50	3.55
B-1-28-7-L-DS	Gr. 8	10.14	13.850	249.55	II & I	72.50	3.44
B-1-28-8-L-DS	"	10.14	12.950	233.33	II & I	72.50	3.22
B-1-39-3-L-DS	Gr. 8	8.07	2.500	322.58	II & I	111.77	2.89
B-1-39-4-L-DS	"	8.07	2.485	320.65	II & I	111.77	2.87
B-1-40-3-L-DS	A307	16.13	4.065	262.26	II & I	111.77	2.35
B-1-40-4-L-DS	"	16.13	3.950	254.84	II & I	111.77	2.28
B-1-40-7-L-DS	Gr. 8	16.13	4.085	263.55	II & I	111.77	2.36
B-1-40-8-L-DS	"	16.13	4.035	260.32	II & I	111.77	2.33
B-1-47-3-L-DS	Gr. 8	7.04	10.100	284.51	II & I	103.92	2.74
B-1-47-4-L-DS	"	7.04	10.575	297.89	II & I	103.92	2.87
B-1-48-3-L-DS	A307	10.56	14.675	275.59	II & I	103.92	2.65
B-1-48-4-L-DS	"	10.56	14.250	267.61	II & I	103.92	2.58
B-1-48-7-L-DS	Gr. 8	10.56	12.920	242.63	II & I	103.92	2.33
B-1-48-8-L-DS	"	10.56	13.850	260.09	II & I	103.92	2.50
Mean Value							3.01
Standard Deviation							0.509
Coefficient of Variation							0.169

Table 6c

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Double Shear With Washers

High Torque

0.024" $\leq$ t < 3/16"

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-1-19-9-H-DS	Gr. 8	6.94	2.435	270.56	II & I	73.28	3.69
B-1-19-10-H-DS	"	6.94	2.325	258.33	II & I	73.28	3.53
B-1-20-9-H-DS	Gr. 8	13.89	4.415	245.28	II & I	73.28	3.35
B-1-20-10-H-DS	"	13.89	4.465	248.06	II & I	73.28	3.39
B-1-27-9-H-DS	Gr. 8	6.76	10.350	279.73	II & I	72.50	3.86
B-1-27-10-H-DS	"	6.76	9.650	260.81	II & I	72.50	3.60
B-1-28-9-H-DS	Gr. 8	10.14	15.700	282.88	II & I	72.50	3.90
B-1-28-10-H-DS	"	10.14	13.650	245.95	II & I	72.50	3.39
B-1-39-5-H-DS	Gr. 8	8.07	2.410	310.97	II & I	111.77	2.78
B-1-40-9-H-DS	Gr. 8	16.13	4.475	288.71	II & I	111.77	2.58
B-1-40-10-H-DS	"	16.13	4.630	298.71	II & I	111.77	2.67
B-1-47-5-H-DS	Gr. 8	7.04	11.425	321.83	II & I	103.92	3.10
B-1-48-9-H-DS	Gr. 8	10.56	15.675	294.37	II & I	103.92	2.83
B-1-48-10-H-DS	"	10.56	13.500	253.52	II & I	103.92	2.44
Mean Value							3.22
Standard Deviation							0.487
Coefficient of Variation							0.151

Table 7a

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Single Shear Without Washers

Zero Torque

$0.036" \leq t < 3/16"$
$F_u/F_y > 1.15$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-0-17-1-0-SS	A307	6.94	1.217	135.22	V	48.85	2.77
B-0-17-2-0-SS	A307	6.94	1.115	123.89	V	48.85	2.54
B-0-17-5-0-SS	Gr. 8	6.94	1.187	131.89	V	48.85	2.70
B-0-17-6-0-SS	"	6.94	1.194	132.67	V	48.85	2.72
B-0-18-1-0-SS	A307	13.89	1.415	78.61	V	48.85	1.61
B-0-18-2-0-SS	"	13.89	1.420	78.89	V	48.85	1.61
B-0-18-5-0-SS	Gr. 8	13.89	1.420	78.88	V	48.85	1.61
B-0-18-6-0-SS	"	13.89	1.596	88.67	V	48.85	1.82
B-0-45-1-0-SS	Gr. 8	7.04	4.040	113.80	V	69.28	1.64
B-0-45-2-0-SS	"	7.04	4.080	114.93	V	69.28	1.66
B-0-46-1-0-SS	A307	10.56	5.825	109.39	II & V	69.28	1.58
B-0-46-2-0-SS	"	10.56	5.470	102.72	II & V	69.28	1.48
B-0-46-5-0-SS	Gr. 8	10.56	5.870	110.23	II & V	69.28	1.59
B-0-46-6-0-SS	"	10.56	5.820	109.30	II & V	69.28	1.58
B-0-51-1-0-SS	Gr. 8	4.08	21.950	159.06	V	70.69	2.25
B-0-51-2-0-SS	"	4.08	21.650	156.88	V	70.69	2.22
Mean Value							1.96
Standard Deviation							0.483
Coefficient of Variation							0.246

Table 7b

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Single Shear Without Washers

Low Torque

0.036" $\leq$ t < 3/16"
$F_u/F_y \geq 1.15$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-0-17-3-L-SS	A307	6.94	1.204	133.78	V	48.85	2.72
B-0-17-4-L-SS	"	6.94	1.292	143.56	V	48.85	2.94
B-0-17-7-L-SS	Gr. 8	6.94	1.195	132.78	V	48.85	2.94
B-0-17-8-L-SS	"	6.94	1.225	136.11	V	48.85	2.79
B-0-18-3-L-SS	A307	13.89	2.040	113.33	V	48.85	2.32
B-0-18-4-L-SS	"	13.89	1.490	82.78	V	48.85	1.69
B-0-18-7-L-SS	Gr. 8	13.89	2.735	151.94	V	48.85	3.11
B-0-18-8-L-SS	"	13.89	2.580	143.33	V	48.85	2.93
B-0-45-3-L-SS	Gr. 8	7.04	4.335	122.11	V	69.28	1.76
B-0-45-4-L-SS	"	7.04	4.325	121.83	V	69.28	1.76
B-0-46-3-L-SS	A307	10.56	6.000	112.68	II & V	69.28	1.63
B-0-46-4-L-SS	"	10.56	5.960	111.92	II & V	69.28	1.62
B-0-46-7-L-SS	Gr. 8	10.56	6.690	125.63	II & V	69.28	1.81
B-0-46-8-L-SS	"	10.56	5.875	110.33	II & V	69.28	1.59
B-0-51-3-L-SS	Gr. 8	4.08	21.150	153.26	V	70.69	2.17
B-0-51-4-L-SS	"	4.08	22.900	165.94	V	70.69	2.35
Mean Value							2.25
Standard Deviation							0.557
Coefficient of Variation							0.248

Table 7c

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Single Shear Without Washers

High Torque

$0.036'' \leq t < 3/16''$
$F_u/F_y > 1.15$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-0-17-9-H-SS	Gr. 8	6.94	1.198	133.11	V	48.85	2.72
B-0-17-10-H-SS	"	6.94	1.214	134.89	V	48.85	2.76
B-0-18-9-H-SS	Gr. 8	13.89	2.610	145.00	V	48.85	2.97
B-0-18-10-H-SS	"	13.89	2.340	130.00	V	48.85	2.66
B-0-45-5-H-SS	Gr. 8	7.04	4.460	125.63	V	69.28	1.81
B-0-45-6-H-SS	"	7.04	4.450	125.35	V	69.28	1.81
B-0-46-9-H-SS	Gr. 8	10.56	7.500	140.85	II & V	69.28	2.03
B-0-46-10-H-SS	"	10.56	6.560	123.19	II & V	69.28	1.78
B-0-51-5-H-SS	Gr. 8	4.08	21.350	154.71	V	70.69	2.19
B-0-51-6-H-SS	"	4.08	22.000	159.42	V	70.69	2.26
Mean Value							2.30
Standard Deviation							0.448
Coefficient of Variation							0.195

Table 8a

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Double Shear Without Washers

Zero Torque

0.036" < t < 3/16"
$F_u/F_y \geq 1.15$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-0-21-1-0-DS	A307	6.94	1.880	208.89	II & I	65.95	3.17
B-0-21-2-0-DS	"	6.94	1.900	211.11	II & I	65.95	3.20
B-0-21-5-0-DS	Gr. 8	6.94	1.940	215.56	II & I	65.95	3.27
B-0-21-6-0-DS	"	6.94	2.030	225.56	II & I	65.95	3.42
B-0-22-1-0-DS	A307	13.89	2.560	146.22	II & I	65.95	2.22
B-0-22-2-0-DS	"	13.89	2.485	138.06	II & I	65.95	2.09
B-0-22-5-0-DS	Gr. 8	13.89	2.425	134.72	II & I	65.95	2.04
B-0-22-6-0-DS	"	13.89	2.200	122.22	II & I	65.95	1.85
B-0-49-1-0-DS	Gr. 8	7.04	9.575	269.72	II & I	93.53	2.88
B-0-49-2-0-DS	"	7.04	8.400	236.62	II & I	93.53	2.53
B-0-50-2-0-DS	A307	10.56	12.25	230.05	II & I	93.53	2.46
B-0-50-2-0-DS	"	10.56	11.90	223.47	II & I	93.53	2.39
B-0-50-5-0-DS	Gr. 8	10.56	11.35	213.15	II & I	93.53	2.28
B-0-50-6-0-DS	"	10.56	10.85	203.76	II & I	93.53	2.18
B-0-53-1-0-DS	Gr. 8	4.08	35.50	257.25	II & I	95.43	2.70
B-0-53-2-0-DS	"	4.08	34.90	252.90	II & I	95.43	2.65
Mean Value							2.58
Standard Deviation							0.484
Coefficient of Variation							0.188

Table 8b

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Double Shear Without Washers

Low Torque

$0.036" \leq t < 3/16"$
$F_u/F_y \geq 1.15$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-0-21-3-L-DS	A307	6.94	1.900	211.11	II & I	65.95	3.20
B-0-21-4-L-DS	"	6.94	1.915	212.78	II & I	65.95	3.23
B-0-21-7-L-DS	Gr. 8	6.94	2.175	241.67	II & I	65.95	3.66
B-0-21-8-L-DS	"	6.94	2.050	227.78	II & I	65.95	3.45
B-0-22-3-L-DS	A307	13.89	2.875	159.72	II & I	65.95	2.42
B-0-22-4-L-DS	"	13.89	2.425	134.72	II & I	65.95	2.04
B-0-22-7-L-DS	Gr. 8	13.89	2.700	150.00	II & I	65.95	2.27
B-0-22-8-L-DS	"	13.89	2.720	151.11	II & I	65.95	2.29
B-0-49-3-L-DS	Gr. 8	7.04	8.820	248.45	II & I	93.53	2.66
B-0-49-4-L-DS	"	7.04	8.950	252.11	II & I	93.53	2.70
B-0-50-3-L-DS	A307	10.56	12.45	233.80	II & I	93.53	2.50
B-0-50-4-L-DS	"	10.56	11.65	218.78	II & I	93.53	2.34
B-0-50-7-L-DS	Gr. 8	10.56	12.00	225.35	II & I	93.53	2.41
B-0-50-8-L-DS	"	10.56	10.08	189.30	II & I	93.53	2.02
B-0-53-3-L-DS	Gr. 8	4.08	36.40	263.77	II & I	95.43	2.76
B-0-53-4-L-DS	"	4.08	36.15	261.96	II & I	95.43	2.75
Mean Value							2.67
Standard Deviation							0.489
Coefficient of Variation							0.183

Table 8c

Computed Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification
Double Shear Without Washers

High Torque

$0.036" \leq t < 3/16"$
$F_u/F_y \geq 1.15$

Specimen No.	Type of Bolt	d/t	P_u (kips)	$(\sigma_b)_{test}$ (ksi)	Failure Type	$(\sigma_b)_{allow}$ (ksi)	$\frac{(\sigma_b)_{test}}{(\sigma_b)_{allow}}$
B-0-21-9-H-DS	Gr. 8	6.94	2.235	248.33	II & I	65.95	3.77
B-0-21-10-H-DS	"	6.94	2.000	222.22	II & I	65.95	3.37
B-0-22-9-H-DS	Gr. 8	13.89	2.650	147.22	II & I	65.95	2.23
B-0-22-10-H-DS	"	13.89	2.860	158.89	II & I	65.95	2.41
B-0-49-5-H-DS	Gr. 8	7.04	9.200	259.15	II & I	93.53	2.77
B-0-49-6-H-DS	"	7.04	9.500	267.61	II & I	93.53	2.86
B-0-50-9-H-DS	Gr. 8	10.56	14.000	262.91	II & I	93.53	2.81
B-0-50-10-H-DS	"	10.56	14.025	263.38	II & I	93.53	2.82
B-0-53-5-H-DS	Gr. 8	4.08	36.100	261.59	II & I	95.43	2.74
Mean Value							2.86
Standard Deviation							0.463
Coefficient of Variation							0.162

Table 9

Average Factor of Safety Based on the Revised Section 4.5.6 of the AISI Specification on Allowable Bearing Stress for Bolted Connections[6]

Type of Connection	Type of Torque		
	Zero Torque	Low Torque (Refer to Table 1a)	High Torque (Refer to Table 1b)
Single shear with washers For 0.024" $\leq$ t < 3/16"	2.10 (0.218)	2.22 (0.233)	2.36 (0.202)
Double shear with washers For 0.024" $\leq$ t < 3/16"	2.42 (0.191)	3.01 (0.169)	3.22 (0.151)
Single shear without washers For 0.036" $\leq$ t < 3/16" and $F_u/F_y \geq 1.15$	1.96 (0.246)	2.25 (0.248)	2.30 (0.195)
Double shear without washers For 0.036" $\leq$ t < 3/16" and $F_u/F_y \geq 1.15$	2.58 (0.188)	2.67 (0.183)	2.86 (0.162)

Note: The values given in the parenthesis are the corresponding coefficients of variation.

Table 10a

Effect of Torques on the Bearing Strength of Single Shear Connections With Washers

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-1-11-1-0-SS B-1-11-2-0-SS	0.014	17.86	119.57	--	--	0.768	--
B-1-11-3-L-SS B-1-11-4-L-SS	0.014	17.86	--	155.72	--	--	--
B-1-11-5-0-SS B-1-11-6-0-SS	0.014	17.86	118.58	--	--	0.737	--
B-1-11-7-L-SS B-1-11-8-L-SS	0.014	17.86	--	161.00	--	--	--
B-1-11-9-H-SS B-1-11-10-H-SS	0.014	17.86	--	--	195.57	--	1.215
B-1-15-1-0-SS B-1-15-2-0-SS	0.036	6.94	172.50	--	--	0.897	--
B-1-15-3-L-SS B-1-15-4-L-SS	0.036	6.94	--	192.23	--	--	--
B-1-15-5-H-SS B-1-15-6-H-SS	0.036	6.94	--	--	204.17	--	1.062

Table 10a

Effect of Torques on the Bearing Strength of Single Shear Connections With Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-1-16-1-0-SS B-1-16-2-0-SS	0.036	13.89	182.78	--	--	1.211	--
B-1-16-3-L-SS B-1-16-4-L-SS	0.036	13.89	--	150.98	--	--	--
B-1-16-5-0-SS B-1-16-6-0-SS	0.036	13.89	109.72	--	--	0.892	--
B-1-16-7-L-SS B-1-16-8-L-SS	0.036	13.89	--	123.06	--	--	--
B-1-16-9-H-SS B-1-16-10-H-SS	0.036	13.89	--	--	153.61	--	1.248
B-1-23-1-0-SS B-1-23-2-0-SS	0.074	6.76	190.10	--	--	0.926	--
B-1-23-3-L-SS B-1-23-4-L-SS	0.074	6.76	--	205.27	--	--	--
B-1-23-5-H-SS B-1-23-6-H-SS	0.074	6.76	--	--	213.32	--	1.039

Table 10a

Effect of Torques on the Bearing Strength of Single Shear Connections With Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-1-24-1-0-SS B-1-24-2-0-SS	0.074	10.14	164.64	--	--	0.852	--
B-1-24-3-L-SS B-1-24-4-L-SS	0.074	10.14	--	193.25	--	--	--
B-1-24-5-0-SS B-1-24-6-0-SS	0.074	10.14	129.28	--	--	1.000	--
B-1-24-7-L-SS B-1-24-8-L-SS	0.074	10.14	--	129.28	--	--	--
B-1-24-9-H-SS B-1-24-10-H-SS	0.074	10.14	--	--	150.45	--	1.164
B-1-31-1-0-SS B-1-31-2-0-SS	0.0154	16.23	185.46	--	--	0.803	--
B-1-31-3-L-SS B-1-31-4-L-SS	0.0154	16.23	--	230.92	--	--	--
B-1-31-5-0-SS B-1-31-6-0-SS	0.0154	16.23	178.71	--	--	0.829	--
B-1-31-7-L-SS B-1-31-8-L-SS	0.0154	16.23	--	215.58	--	--	--
B-1-31-9-H-SS B-1-31-10-H-SS	0.0154	16.23	--	--	259.35	--	1.203

Table 10a

Effect of Torques on the Bearing Strength of
Single Shear Connections With Washers
(cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-1-35-1-O-SS B-1-35-2-O-SS	0.031	8.07	250.58	--	--	1.001	--
B-1-35-3-L-SS B-1-35-4-L-SS	0.031	8.07	--	250.33	--	--	--
B-1-35-5-H-SS B-1-35-6-H-SS	0.031	8.07	--	--	264.52	--	1.057
B-1-36-1-O-SS B-1-36-2-O-SS	0.031	16.13	164.20	--	--	0.863	--
B-1-36-3-L-SS B-1-36-4-L-SS	0.031	16.13	--	190.33	--	--	--
B-1-36-5-O-SS B-1-36-6-O-SS	0.031	16.13	150.32	--	--	0.967	--
B-1-36-7-L-SS B-1-36-8-L-SS	0.031	16.13	--	155.49	--	--	--
B-1-36-9-H-SS B-1-36-10-H-SS	0.031	16.13	--	--	207.42	--	1.334

Table 10a

Effect of Torques on the Bearing Strength of
Single Shear Connections With Washers
(cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-1-43-1-0-SS B-1-43-2-0-SS	0.071	7.04	189.93	--	--	0.884	--
B-1-43-3-L-SS B-1-43-4-L-SS	0.071	7.04	--	214.79	--	--	--
B-1-43-5-H-SS B-1-43-6-H-SS	0.071	7.04	--	--	193.24	--	0.900
B-1-44-1-0-SS	0.071	10.56	208.45	--	--	0.935	--
B-1-44-3-L-SS B-1-44-4-L-SS	0.071	10.56	--	233.01	--	--	--
B-1-44-5-0-SS B-1-44-6-0-SS	0.071	10.56	153.99	--	--	1.015	--
* B-1-44-7-L-SS * B-1-44-8-L-SS	0.071	10.56	--	151.64	--	--	--
B-1-44-9-H-SS B-1-44-10-H-SS	0.071	10.56	--	--	157.28	--	1.037

*Unreasonable test result

Table 10b

Effect of Torques on the Bearing Strength of Double Shear Connections With Washers

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-1-13-1-0-DS B-1-13-2-0-DS	0.014	17.86	144.72	--	--	0.651	--
B-1-13-3-L-DS B-1-13-4-0-DS	0.014	17.86	--	222.14	--	--	--
B-1-13-5-0-DS B-1-13-6-0-DS	0.014	17.86	151.14	--	--	0.672	--
B-1-13-7-L-DS B-1-13-8-L-DS	0.014	17.86	--	225.00	--	--	--
B-1-13-9-H-DS B-1-13-10-H-DS	0.014	17.86	--	--	237.29	--	1.055
B-1-19-1-0-DS B-1-19-2-0-DS	0.036	6.94	207.50	--	--	0.887	--
B-1-19-3-L-DS B-1-19-4-L-DS	0.036	6.94	--	233.89	--	--	--
B-1-19-5-0-DS B-1-19-6-0-DS	0.036	6.94	195.00	--	--	0.847	--
B-1-19-7-L-DS B-1-19-8-L-DS	0.036	6.94	--	230.28	--	--	--
B-1-19-9-H-DS B-1-19-10-H-DS	0.036	6.94	--	--	264.45	--	1.148

Table 10b

Effect of Torques on the Bearing Strength of
Double Shear Connections With Washers
(cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-1-20-1-0-DS B-1-20-2-0-DS	0.036	13.89	165.97	--	--	0.787	--
B-1-20-3-L-DS B-1-20-4-L-DS	0.036	13.89	--	210.97	--	--	--
B-1-20-5-0-DS B-1-20-6-0-DS	0.036	13.89	174.17	--	--	0.763	--
B-1-20-8-L-DS	0.036	13.89	--	228.33	--	--	--
B-1-20-9-H-DS B-1-20-10-H-DS	0.036	13.89	--	--	246.67	--	1.080
B-1-27-1-0-DS B-1-27-2-0-DS	0.074	6.76	199.39	--	--	0.709	--
B-1-27-3-L-DS B-1-27-4-L-DS	0.074	6.76	--	281.09	--	--	--
B-1-27-5-0-DS B-1-27-6-0-DS	0.074	6.76	200.34	--	--	0.723	--
B-1-27-7-L-DS B-1-27-8-L-DS	0.074	6.76	--	277.03	--	--	--
B-1-27-9-H-DS B-1-27-10-H-DS	0.074	6.76	--	--	270.27	--	0.976

Table 10b

Effect of Torques on the Bearing Strength of
Double Shear Connections With Washers
(cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-1-28-1-0-DS B-1-28-2-0-DS	0.074	10.14	217.57	--	--	0.870	--
B-1-28-3-L-DS B-1-28-4-L-DS	0.074	10.14	--	250.00	--	--	--
B-1-28-5-0-DS B-1-28-6-0-DS	0.074	10.14	204.51	--	--	0.847	--
B-1-28-7-L-DS B-1-28-8-L-DS	0.074	10.14	--	241.44	--	--	--
B-1-28-9-H-DS B-1-28-10-H-DS	0.074	10.14	--	--	264.42	--	1.095
B-1-33-1-0-DS B-1-33-2-0-DS	0.0154	16.23	181.56	--	--	0.729	--
B-1-33-3-L-DS B-1-33-4-L-DS	0.0154	16.23	--	248.96	--	--	--
B-1-33-5-0-DS B-1-33-6-0-DS	0.0154	16.23	189.10	--	--	0.658	--
B-1-33-7-L-DS B-1-33-8-L-DS	0.0154	16.23	--	287.53	--	--	--
B-1-33-9-H-DS B-1-33-10-H-DS	0.0154	16.23	--	--	310.26	--	1.079

Table 10b

Effect of Torques on the Bearing Strength of Double Shear Connections With Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-1-39-1-0-DS B-1-39-2-0-DS	0.031	8.07	222.58	--	--	0.692	--
B-1-39-3-L-DS B-1-39-4-L-DS	0.031	8.07	--	321.62	--	--	--
B-1-39-5-H-DS	0.031	8.07	--	--	310.97	--	0.967
B-1-40-1-0-DS B-1-40-2-0-DS	0.031	16.13	180.16	--	--	0.697	--
B-1-40-3-L-DS B-1-40-4-L-DS	0.031	16.13	--	258.55	--	--	--
B-1-40-5-0-DS B-1-40-6-0-DS	0.031	16.13	181.62	--	--	0.693	--
B-1-40-7-L-DS B-1-40-8-L-DS	0.031	16.13	--	261.94	--	--	--
B-1-40-9-H-DS B-1-40-10-H-DS	0.031	16.13	--	--	293.71	--	1.121

Table 10b

Effect of Torques on the Bearing Strength of Double Shear Connections With Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-1-47-1-0-DS B-1-47-2-0-DS	0.071	7.04	283.03	--	--	0.972	--
B-1-47-3-L-DS B-1-47-4-L-DS	0.071	7.04	--	291.20	--	--	--
B-1-47-5-H-DS	0.071	7.04	--	--	321.83	--	1.105
B-1-48-1-0-DS B-1-48-2-0-DS	0.071	10.56	226.29	--	--	0.833	--
B-1-48-3-L-DS B-1-48-4-L-DS	0.071	10.56	--	271.60	--	--	--
B-1-48-5-0-DS B-1-48-6-0-DS	0.071	10.56	240.38	--	--	0.956	--
B-1-48-7-L-DS B-1-48-8-L-DS	0.071	10.56	--	251.36	--	--	--
B-1-48-9-H-DS B-1-48-10-H-DS	0.071	10.56	--	--	273.95	--	1.090

Table 10b

Effect of Torques on the Bearing Strength of Double Shear Connections With Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_L$		
B-1-52-1-0-DS B-1-52-2-0-DS	0.184	4.08	255.62	--	--	0.962	--
B-1-52-3-L-DS B-1-52-4-L-DS	0.184	4.08	--	265.76	--	--	--
B-1-52-5-H-DS	0.184	40.8	--	--	259.42	--	0.976

Table 10c

Effect of Torques on the Bearing Strength of Single Shear Connections Without Washers

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-O-12-1-O-SS B-O-12-2-O-SS	0.014	17.86	100.43	--	--	1.077	--
B-O-12-3-L-SS B-O-12-4-L-SS	0.014	17.86	--	93.29	--	--	--
B-O-12-5-O-SS B-O-12-6-O-SS	0.014	17.86	89.72	--	--	0.921	--
B-O-12-7-L-SS B-O-12-8-L-SS	0.014	17.86	--	97.43	--	--	--
B-O-12-9-H-SS B-O-12-10-H-SS	0.014	17.86	--	--	109.43	--	1.123
B-O-17-1-O-SS B-O-17-2-O-SS	0.036	6.94	129.56	--	--	0.934	--
B-O-17-3-L-SS B-O-17-4-L-SS	0.036	6.94	--	138.67	--	--	--
B-O-17-5-O-SS B-O-17-6-O-SS	0.036	6.94	132.28	--	--	0.984	--
B-O-17-7-L-SS B-O-17-8-L-SS	0.036	6.94	--	134.45	--	--	--
B-O-17-9-H-SS B-O-17-10-H-SS	0.036	6.94	--	--	134.00	--	0.997

Table 10c

Effect of Torques on the Bearing Strength of
Single Shear Connections Without Washers
(cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-O-18-1-O-SS B-O-18-2-O-SS	0.036	13.89	78.75	--	--	0.803	--
B-O-18-3-L-SS B-O-18-4-L-SS	0.036	13.89	--	98.06	--	--	--
B-O-18-5-O-SS B-O-18-6-O-SS	0.036	13.89	83.78	--	--	0.567*	--
B-O-18-7-L-SS B-O-18-8-L-SS	0.036	13.89	--	147.64	--	--	--
B-O-18-9-H-SS B-O-18-10-H-SS	0.036	13.89	--	--	137.50	--	0.931
B-O-25-1-O-SS B-O-25-2-O-SS	0.074	6.76	112.98	--	--	0.902	--
B-O-25-3-L-SS B-O-25-4-L-SS	0.074	6.76	--	125.27	--	--	--
B-O-25-5-H-SS B-O-25-6-H-SS	0.074	6.76	--	--	120.81	--	0.964

Table 10c

Effect of Torques on the Bearing Strength of Single Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-O-26-1-O-SS B-O-26-2-O-SS	0.074	10.14	99.42	--	--	0.983	--
B-O-26-3-L-SS B-O-26-4-L-SS	0.074	10.14	--	101.17	--	--	--
B-O-26-5-O-SS B-O-26-6-O-SS	0.074	10.14	96.67	--	--	0.956	--
B-O-26-7-L-SS B-O-26-8-L-SS	0.074	10.14	--	101.08	--	--	--
B-O-26-9-H-SS B-O-26-10-H-SS	0.074	10.14	--	--	129.28	--	1.279
B-O-32-1-O-SS B-O-32-2-O-SS	0.0154	16.23	146.76	--	--	0.857	--
B-O-32-3-L-SS B-O-32-4-L-SS	0.0154	16.23	--	171.17	--	--	--
B-O-32-5-O-SS B-O-32-6-O-SS	0.0154	16.23	148.31	--	--	1.041	--
B-O-32-7-L-SS B-O-32-8-L-SS	0.0154	16.23	--	142.47	--	--	--
B-O-32-9-H-SS B-O-32-10-H-SS	0.0154	16.23	--	--	189.87	--	1.333

Table 10c

Effect of Torques on the Bearing Strength of Single Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-O-37-1-O-SS B-O-37-2-O-SS	0.031	8.07	155.55	--	--	0.961	--
B-O-37-3-L-SS B-O-37-4-L-SS	0.031	8.07	--	161.94	--	--	--
B-O-37-5-H-SS B-O-37-6-H-SS	0.031	8.07	--	--	157.16	--	0.971
B-O-38-1-O-SS B-O-38-2-O-SS	0.031	16.13	103.55	--	--	0.762	--
B-O-38-3-L-SS B-O-38-4-L-SS	0.031	16.13	--	135.81	--	--	--
B-O-38-5-O-SS B-O-38-6-O-SS	0.031	16.13	106.13	--	--	0.786	--
B-O-38-7-L-SS B-O-38-8-L-SS	0.031	16.13	--	135.00	--	--	--
B-O-38-9-H-SS B-O-38-10-H-SS	0.031	16.13	--	--	142.90	--	1.059

Table 10c

Effect of Torques on the Bearing Strength of Single Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-0-45-1-0-SS B-0-45-2-0-SS	0.071	7.04	114.37	--	--	0.938	--
B-0-45-3-L-SS B-0-45-4-L-SS	0.071	7.04	--	121.97	--	--	--
B-0-45-5-H-SS B-0-45-6-H-SS	0.071	7.04	--	--	125.49	--	1.029
B-0-46-1-0-SS B-0-46-2-0-SS	0.071	10.56	106.06	--	--	0.944	--
B-0-46-3-L-SS B-0-46-4-L-SS	0.071	10.56	--	112.30	--	--	--
B-0-46-5-0-SS B-0-46-6-0-SS	0.071	10.56	109.77	--	--	0.930	--
B-0-46-7-L-SS B-0-46-8-L-SS	0.071	10.56	--	117.98	--	--	--
B-0-46-9-H-SS B-0-46-10-H-SS	0.071	10.56	--	--	132.02	--	1.119

Table 10c

Effect of Torques on the Bearing Strength of Single Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-O-51-1-O-SS B-O-51-2-O-SS	0.184	4.08	157.97	--	--	0.990	--
B-O-51-3-L-SS B-O-51-4-L-SS	0.184	4.08	--	159.60	--	--	--
B-O-51-5-H-SS B-O-51-6-H-SS	0.184	4.08	--	--	157.07	--	0.984

Table 10d

Effect of Torques on the Bearing Strength of Double Shear Connections Without Washers

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-0-14-1-0-DS B-0-14-2-0-DS	0.014	17.86	145.86	--	--	0.925	--
B-0-14-3-L-DS B-0-14-4-L-DS	0.014	17.86	--	157.72	--	--	--
B-0-14-5-0-DS B-0-14-6-0-DS	0.014	17.86	143.57	--	--	0.720	--
B-0-14-7-L-DS B-0-14-8-L-DS	0.014	17.86	--	199.43	--	--	--
B-0-14-9-H-DS B-0-14-10-H-DS	0.014	17.86	--	--	156.29	--	0.784*
B-0-21-1-0-DS B-0-21-2-0-DS	0.036	6.94	210.00	--	--	0.991	--
B-0-21-3-L-DS B-0-21-4-L-DS	0.036	6.94	--	211.95	--	--	--
B-0-21-5-0-DS B-0-21-6-0-DS	0.036	6.94	220.56	--	--	0.940	--
B-0-21-7-L-DS B-0-21-8-L-DS	0.036	6.94	--	234.73	--	--	--
B-0-21-9-H-DS B-0-21-10-H-DS	0.036	6.94	--	--	235.28	--	1.002

Table 10d

Effect of Torques on the Bearing Strength of Double Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_0}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_0$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-0-22-1-0-DS B-0-22-2-0-DS	0.036	13.89	142.14	--	--	0.965	--
B-0-22-3-L-DS B-0-22-4-L-DS	0.036	13.89	--	147.22	--	--	--
B-0-22-5-0-DS B-0-22-6-0-DS	0.036	13.89	128.47	--	--	0.853	--
B-0-22-7-L-DS B-0-22-8-L-DS	0.036	13.89	--	150.56	--	--	--
B-0-22-9-H-DS B-0-22-10-H-DS	0.036	13.89	--	--	153.06	--	1.017
B-0-29-1-0-DS B-0-29-2-0-DS	0.074	6.76	201.69	--	--	0.865	--
B-0-29-3-L-DS B-0-29-4-L-DS	0.074	6.76	--	233.11	--	--	--
B-0-29-5-0-DS B-0-29-6-0-DS	0.074	6.76	207.77	--	--	0.831	--
B-0-29-7-L-DS B-0-29-8-L-DS	0.074	6.76	--	250.00	--	--	--
B-0-29-9-H-DS B-0-29-10-H-DS	0.074	6.76	--	--	248.65	--	0.995

Table 10d

Effect of Torques on the Bearing Strength of Double Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-O-30-1-O-DS B-O-30-2-O-DS	0.074	10.14	184.24	--	--	0.917	--
B-O-30-3-L-DS B-O-30-4-L-DS	0.074	10.14	--	200.91	--	--	--
B-O-30-5-O-DS B-O-30-6-O-DS	0.074	10.14	182.03	--	--	0.921	--
B-O-30-7-L-DS B-O-30-8-L-DS	0.074	10.14	--	197.66	--	--	--
B-O-30-9-H-DS B-O-30-10-H-DS	0.074	10.14	--	--	206.31	--	1.044
B-O-34-1-O-DS B-O-34-2-O-DS	0.0154	16.23	221.69	--	--	0.874	--
B-O-34-3-L-DS B-O-34-4-L-DS	0.0154	16.23	--	253.51	--	--	--
B-O-34-5-O-DS B-O-34-6-O-DS	0.0154	16.23	195.46	--	--	0.789	--
B-O-34-7-L-DS B-O-34-8-L-DS	0.0154	16.23	--	247.79	--	--	--
B-O-34-9-H-DS B-O-34-10-H-DS	0.0154	16.23	--	--	249.55	--	1.007

Table 10d

Effect of Torques on the Bearing Strength of Double Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-O-41-1-O-DS B-O-41-2-O-DS	0.031	8.07	267.42	--	--	0.917	--
B-O-41-3-L-DS B-O-41-4-L-DS	0.031	8.07	--	291.62	--	--	--
B-O-41-5-H-DS B-O-41-6-H-DS	0.031	8.07	--	--	304.52	--	1.044
B-O-42-1-O-DS B-O-42-2-O-DS	0.031	16.13	182.42	--	--	1.008	--
B-O-42-3-L-DS B-O-42-4-L-DS	0.031	16.13	--	180.97	--	--	--
B-O-42-5-O-DS B-O-42-6-O-DS	0.031	16.13	194.19	--	--	0.908	--
B-O-42-7-L-DS B-O-42-8-L-DS	0.031	16.13	--	213.87	--	--	--
B-O-42-9-H-DS B-O-42-10-H-DS	0.031	16.13	--	--	265.00	--	1.239

Table 10d

Effect of Torques on the Bearing Strength of Double Shear Connections Without Washers (cont'd)

Spec. No.	t	d/t	Average of two identical tests			$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
			$(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$		
B-O-49-1-O-DS B-O-49-2-O-DS	0.071	7.04	253.17	--	--	1.012	--
B-O-49-3-L-DS B-O-49-4-L-DS	0.071	7.04	--	250.28	--	--	--
B-O-49-5-H-DS B-O-49-6-H-DS	0.071	7.04	--	--	263.38	--	1.052
B-O-50-1-O-DS B-O-50-2-O-DS	0.071	10.56	226.76	--	--	1.002	--
B-O-50-3-L-DS B-O-50-4-L-DS	0.071	10.56	--	226.29	--	--	--
B-O-50-5-O-DS B-O-50-6-O-DS	0.071	10.56	208.46	--	--	1.005	--
B-O-50-7-L-DS B-O-50-8-L-DS	0.071	10.56	--	207.33	--	--	--
B-O-50-9-H-DS B-O-50-10-H-DS	0.071	10.56	--	--	263.15	--	1.269

Table 10d

Effect of Torques on the Bearing Strength of
Double Shear Connections Without Washers
(cont'd)

Spec. No.	t	d/t	Average of two identical tests $(\sigma_b)_O$	$(\sigma_b)_L$	$(\sigma_b)_H$	$\frac{(\sigma_b)_O}{(\sigma_b)_L}$	$\frac{(\sigma_b)_H}{(\sigma_b)_L}$
B-O-53-1-O-DS B-O-53-2-O-DS	0.184	4.08	255.08	--	--	0.970	--
B-O-53-3-L-DS B-O-53-4-L-DS	0.184	4.08	--	262.87	--	--	--
B-O-53-5-H-DS	0.184	4.08	--	--	267.59	--	1.0180

*Unreasonable test result

Table 11a

Effect of Washers on the Bearing Strength of Single Shear Connections

Specimen No. (See Note No. 2 of Table 3a)	t (In.)	d/t	Average Ratio of $\frac{(\sigma_b) \text{ with washers}}{(\sigma_b) \text{ without washers}}$		
			Zero Torque	Low Torque	High Torque
11 & 12	0.014	17.86	1.26	1.66	1.79
15 & 17	0.036	6.94	1.30	1.43	1.52
16 & 18	0.036	13.89	1.31	1.54	1.12
23 & 25	0.074	6.76	1.68	1.64	1.77
24 & 26	0.074	10.14	1.50	1.59	1.16
31 & 32	0.0154	16.23	1.23	1.43	1.37
35 & 37	0.031	8.07	1.61	1.55	1.68
36 & 38	0.031	16.13	1.50	1.28	1.45
43 & 45	0.071	7.04	1.66	1.76	1.54
44 & 46	0.071	10.56	1.68	1.64	1.19

Table 11b

Effect of Washers on the Bearing Strength of Double Shear Connections

Specimen No. (See Note No. 2 of Table 3a)	t (In.)	d/t	Average Ratio of $\frac{(\sigma_b) \text{ with washers}}{(\sigma_b) \text{ without washers}}$		
			Zero Torque	Low Torque	High Torque
13 & 14	0.014	17.86	1.02	1.27	1.52
19 & 21	0.036	6.94	0.94	1.04	1.12
20 & 22	0.036	13.89	1.26	1.47	1.61
27 & 29	0.074	6.76	0.98	1.16	1.09
28 & 30	0.074	10.14	1.15	1.23	1.28
33 & 34	0.0154	16.23	0.89	1.07	1.24
39 & 41	0.031	8.07	0.83	1.10	1.02
47 & 49	0.071	7.04	1.12	1.16	1.22
48 & 50	0.071	10.56	1.08	1.21	1.04
52 & 53	0.184	4.08	1.00	1.01	0.97

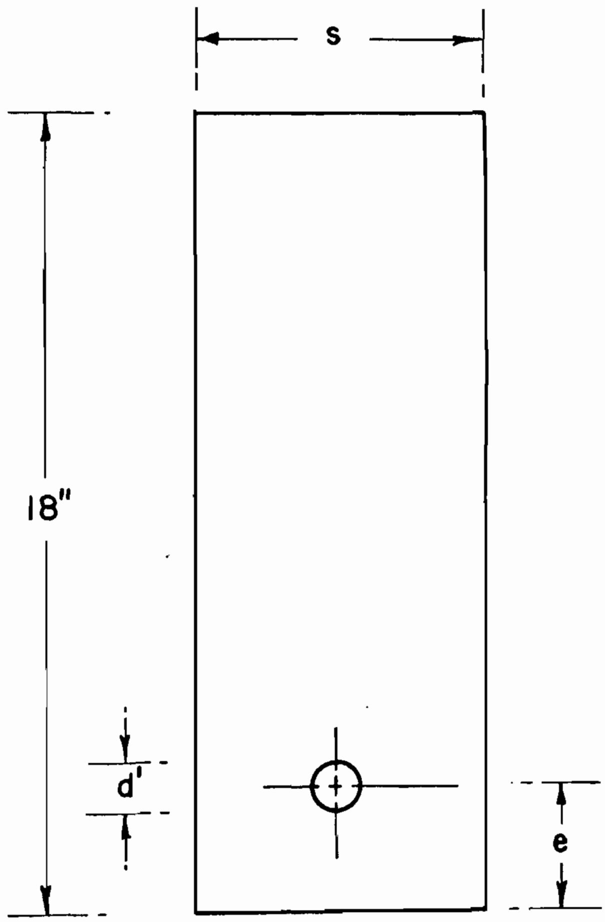

Figure 1. Definition of Symbols used in Table 3a

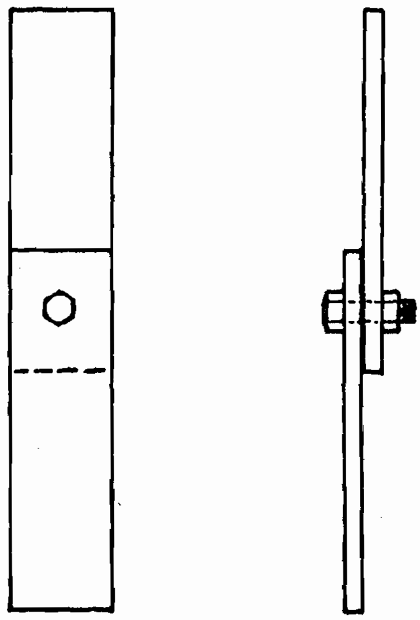

Figure 2. Test Assembly for Single Shear Connections

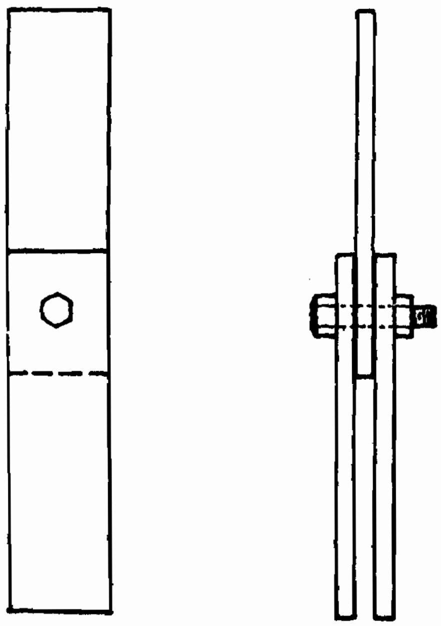

Figure 3. Test Assembly for Double Shear Connections

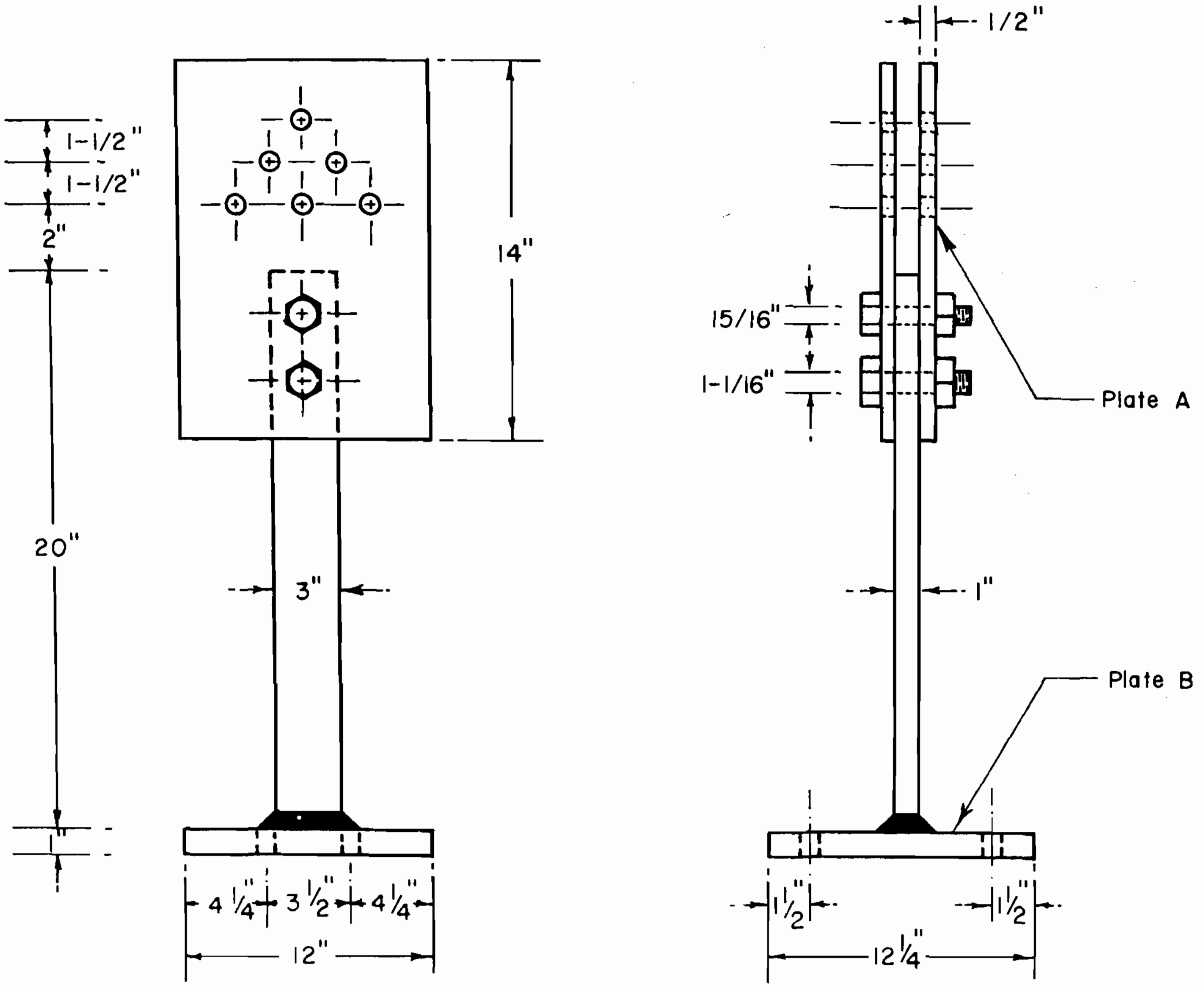

Figure 4. Supporting Unit

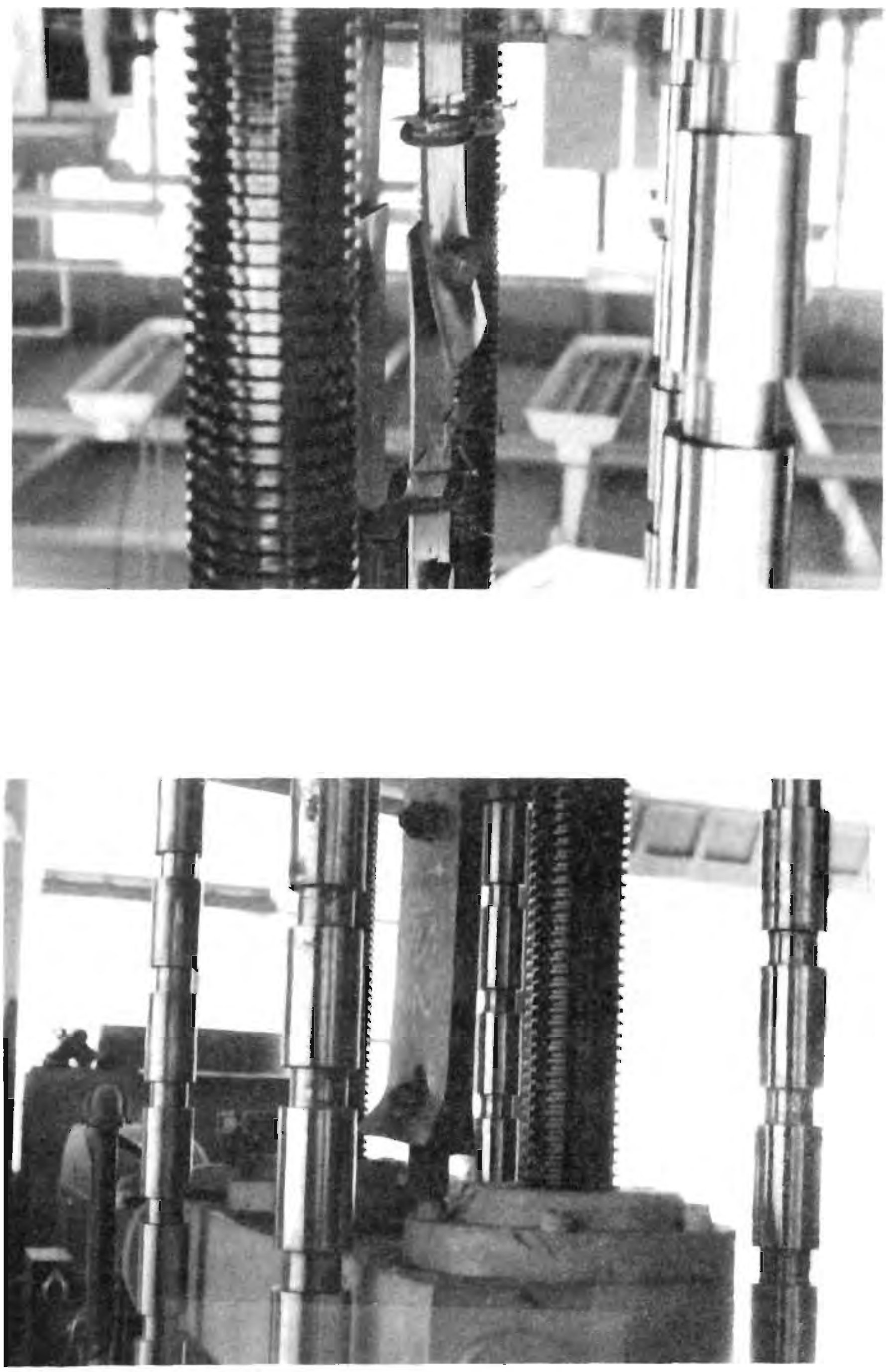

Figure 5. Photographs of the Typical Failure Modes due to Excessive Bolt Rotation and Dishing of Steel Sheets

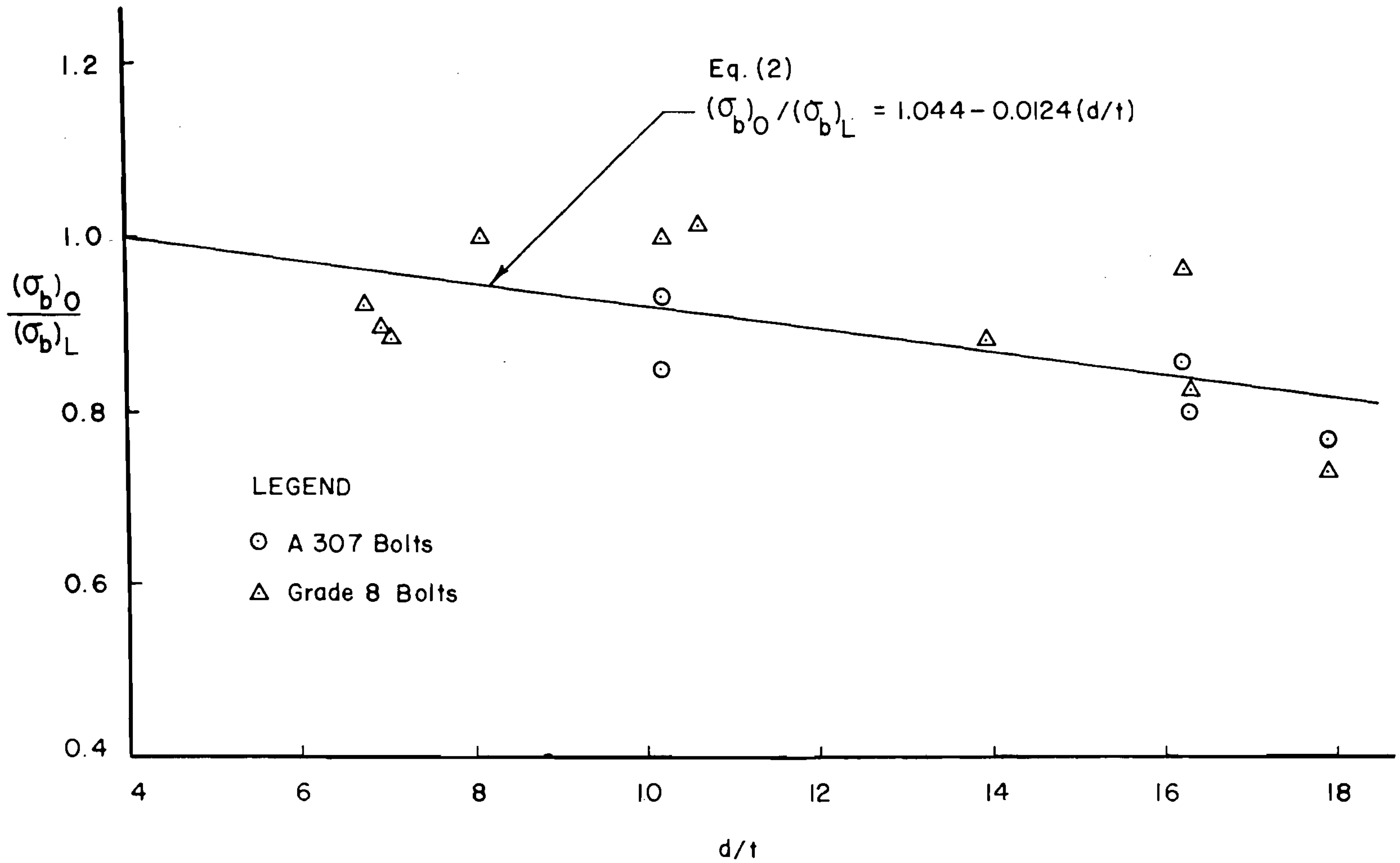

Figure 6. Effect of d/t on the Ratio of $(\sigma_b)_O/(\sigma_b)_L$ for Single Shear Connections with Washers

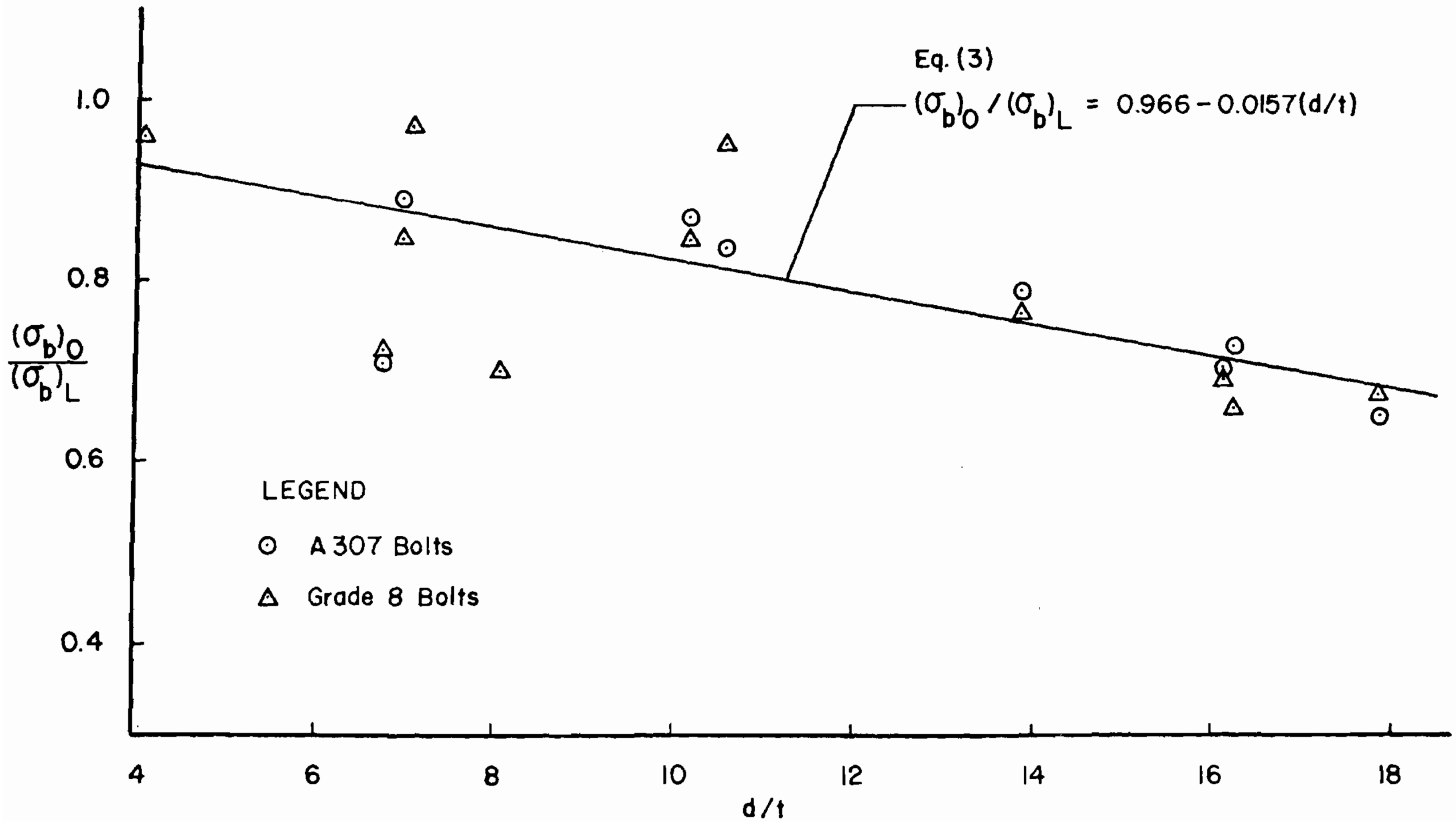

Figure 7. Effect of d/t on the Ratio of $(\sigma_b)_O/(\sigma_b)_L$ for Double Shear Connections with Washers

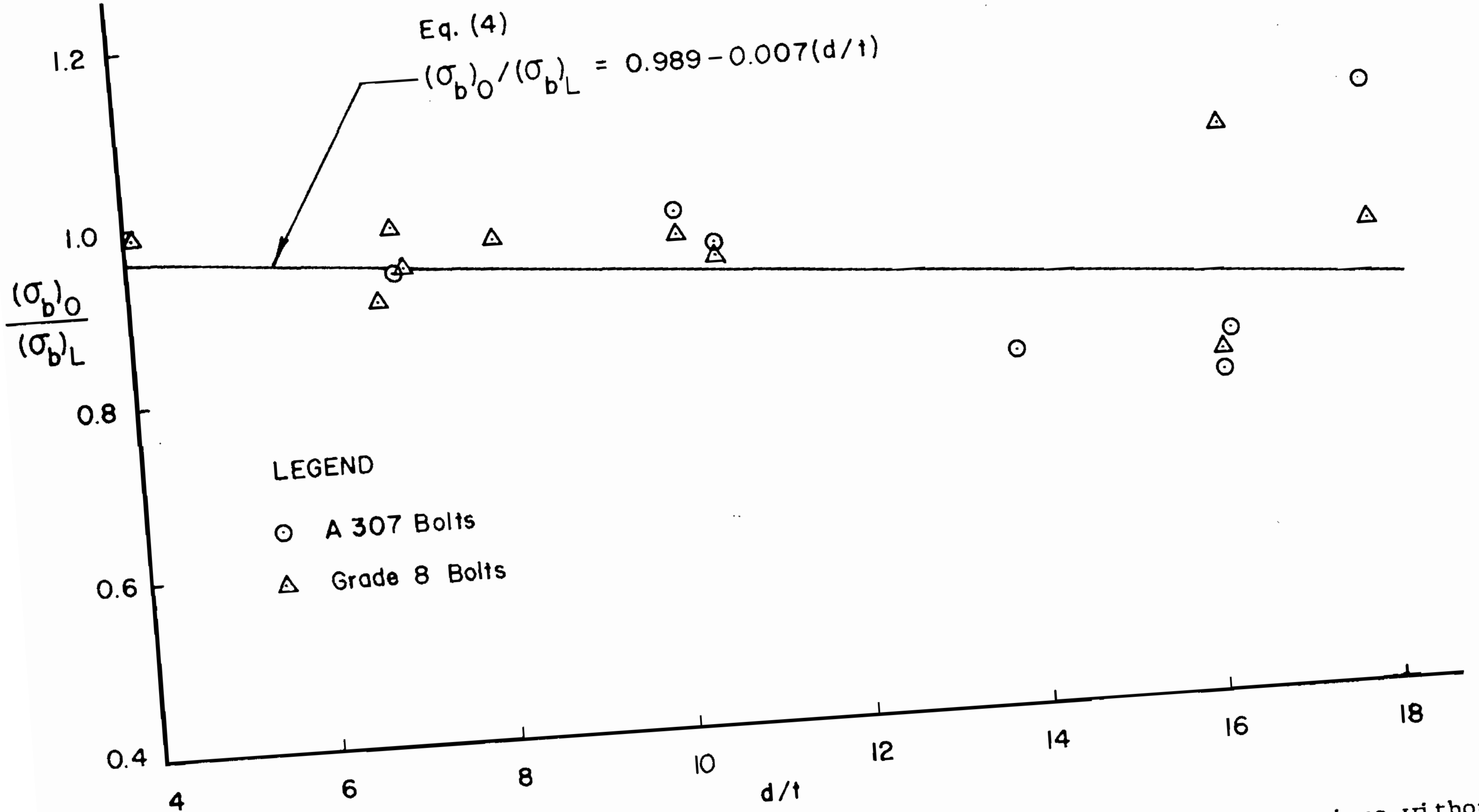

Figure 8. Effect of d/t on the Ratio of $(\sigma_b)_O/(\sigma_b)_L$ for Single Shear Connections without Washers

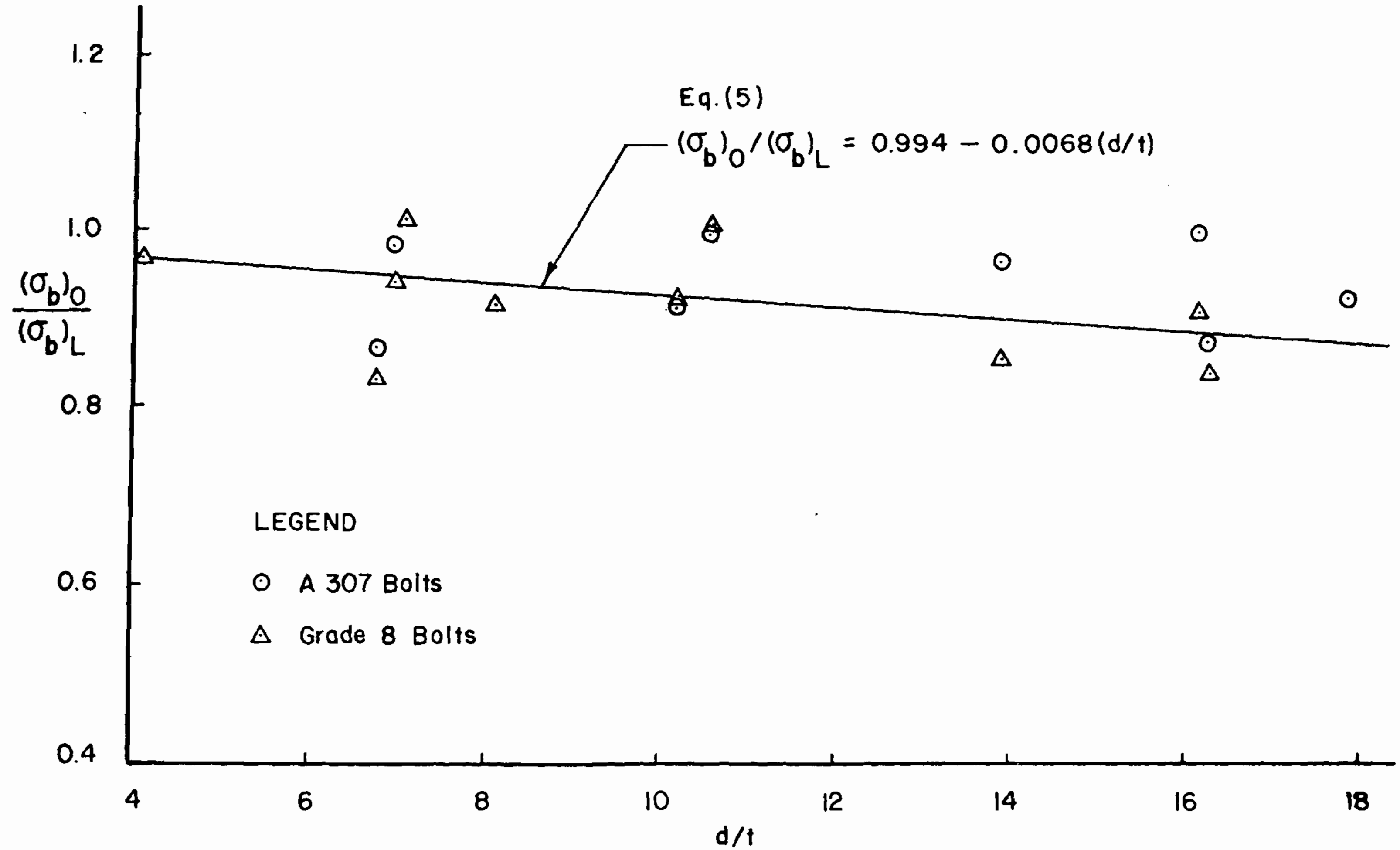

Figure 9. Effect of d/t on the Ratio of $(\sigma_b)_O/(\sigma_b)_L$ for Double Shear Connections without Washers

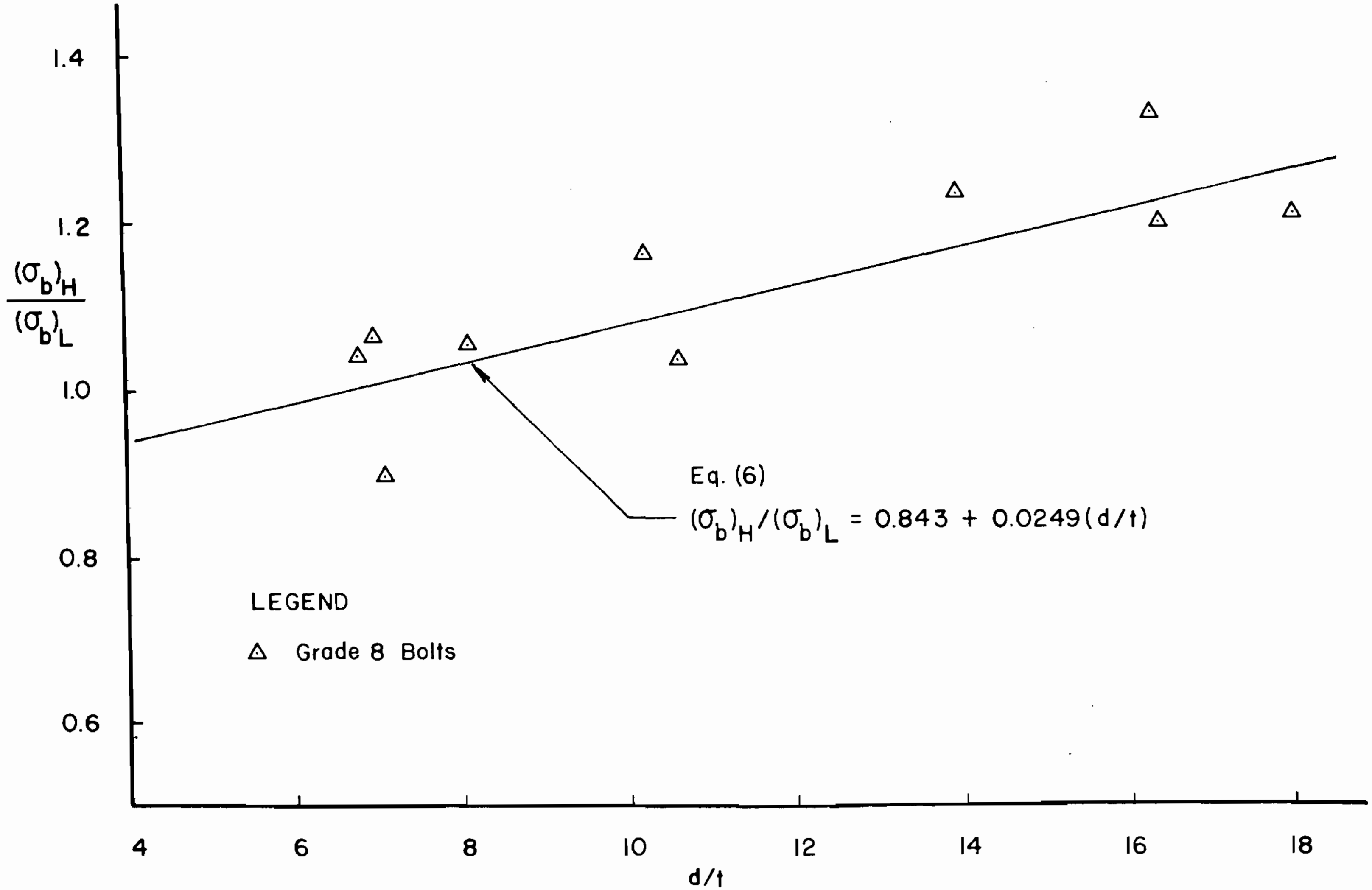

Figure 10. Effect of d/t on the Ratio of $(\sigma_b)_H/(\sigma_b)_L$ for Single Shear Connections with Washers, Grade 8 Bolts

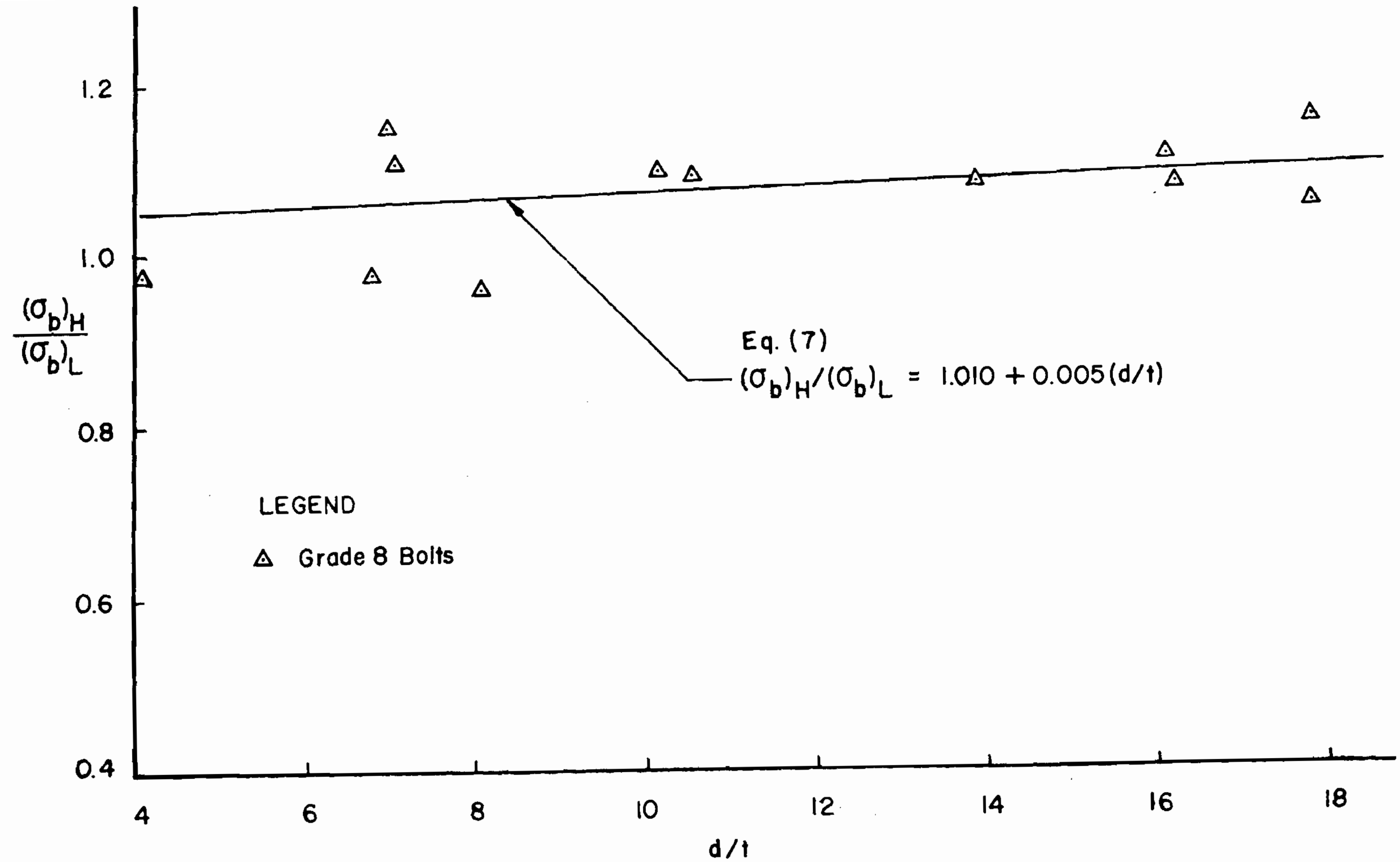

Figure 11. Effect of d/t on the Ratio of $(\sigma_b)_H/(\sigma_b)_L$ for Double Shear Connections with Washers, Grade 8 Bolts

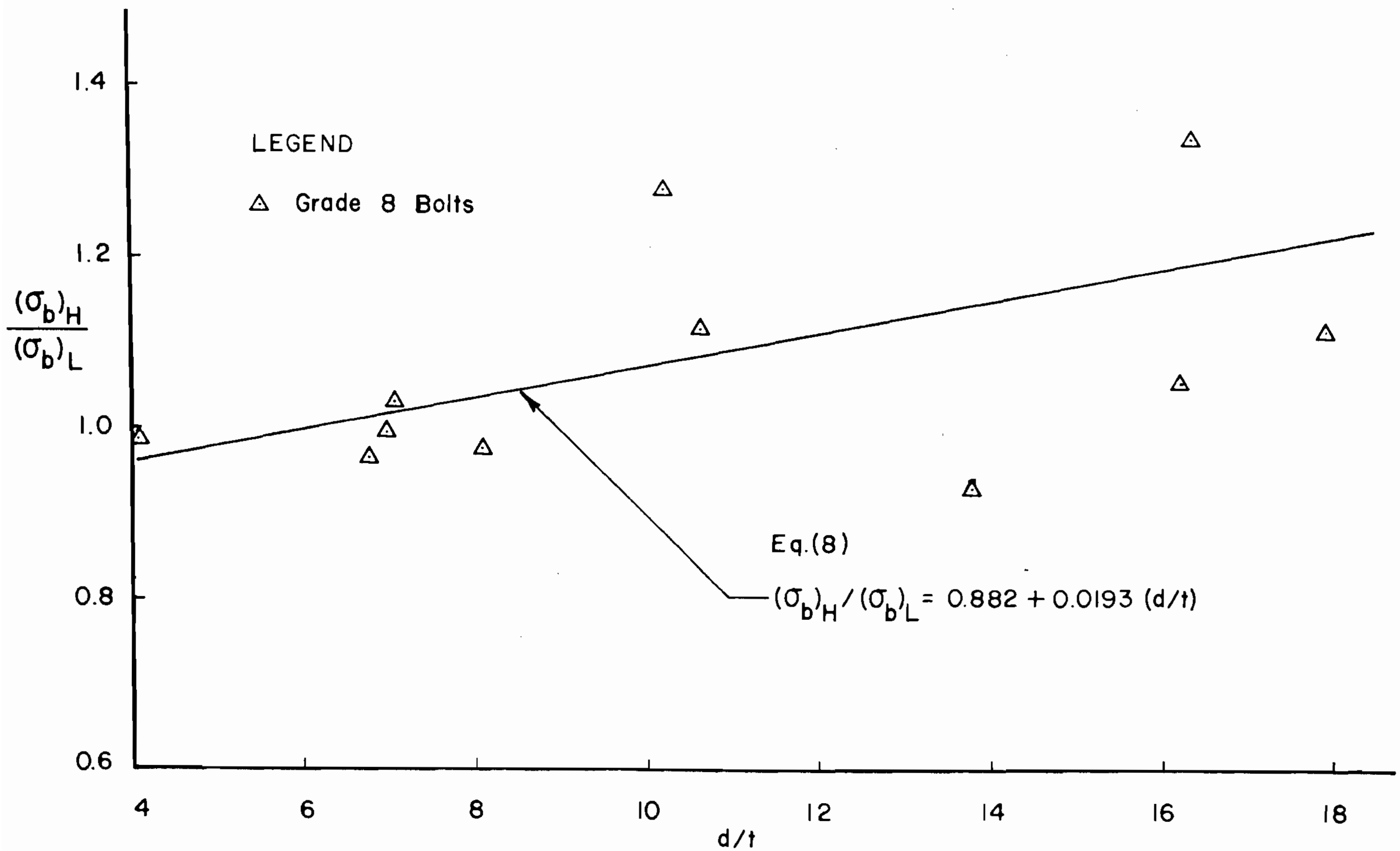

Figure 12. Effect of d/t on the Ratio of $(\sigma_b)_H/(\sigma_b)_L$ for Single Shear Connections without Washers, Grade 8 Bolts

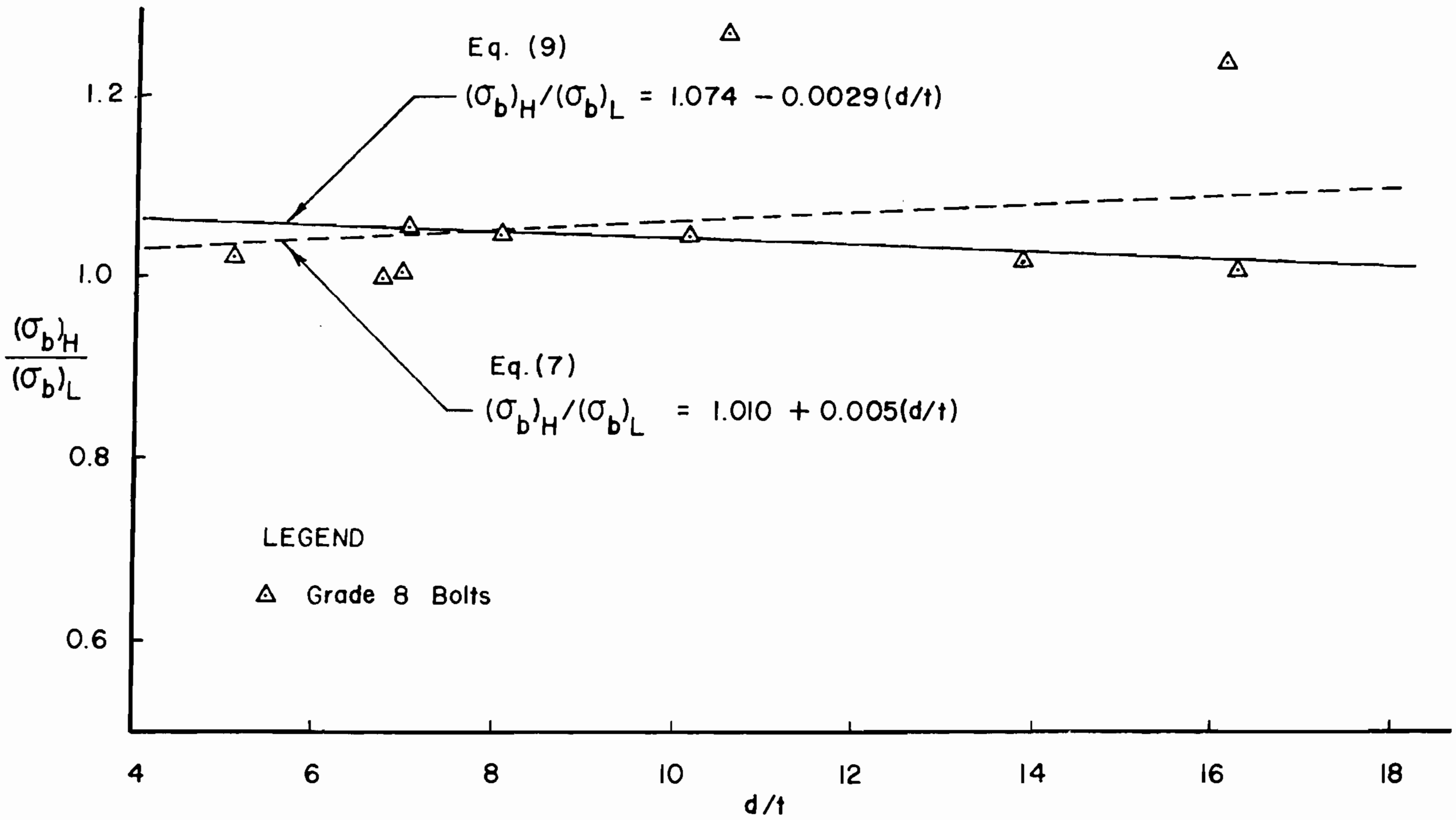

Figure 13. Effect of d/t on the Ratio of $(\sigma_b)_H/(\sigma_b)_L$ for Double Shear Connections without Washers

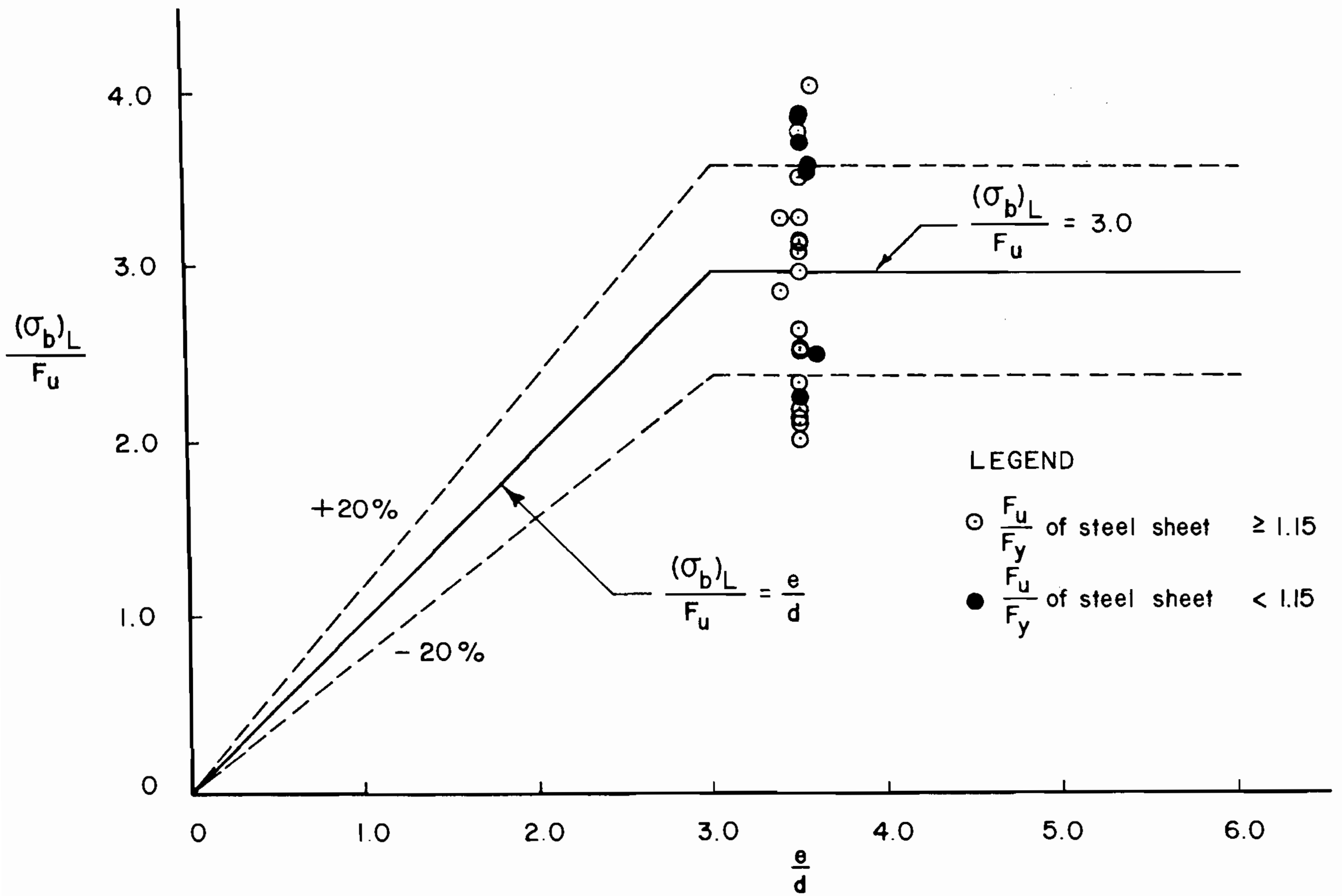

Figure 14. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Single Shear Connections with Washers, $0.024 \leq t < \frac{3}{16}$ in.

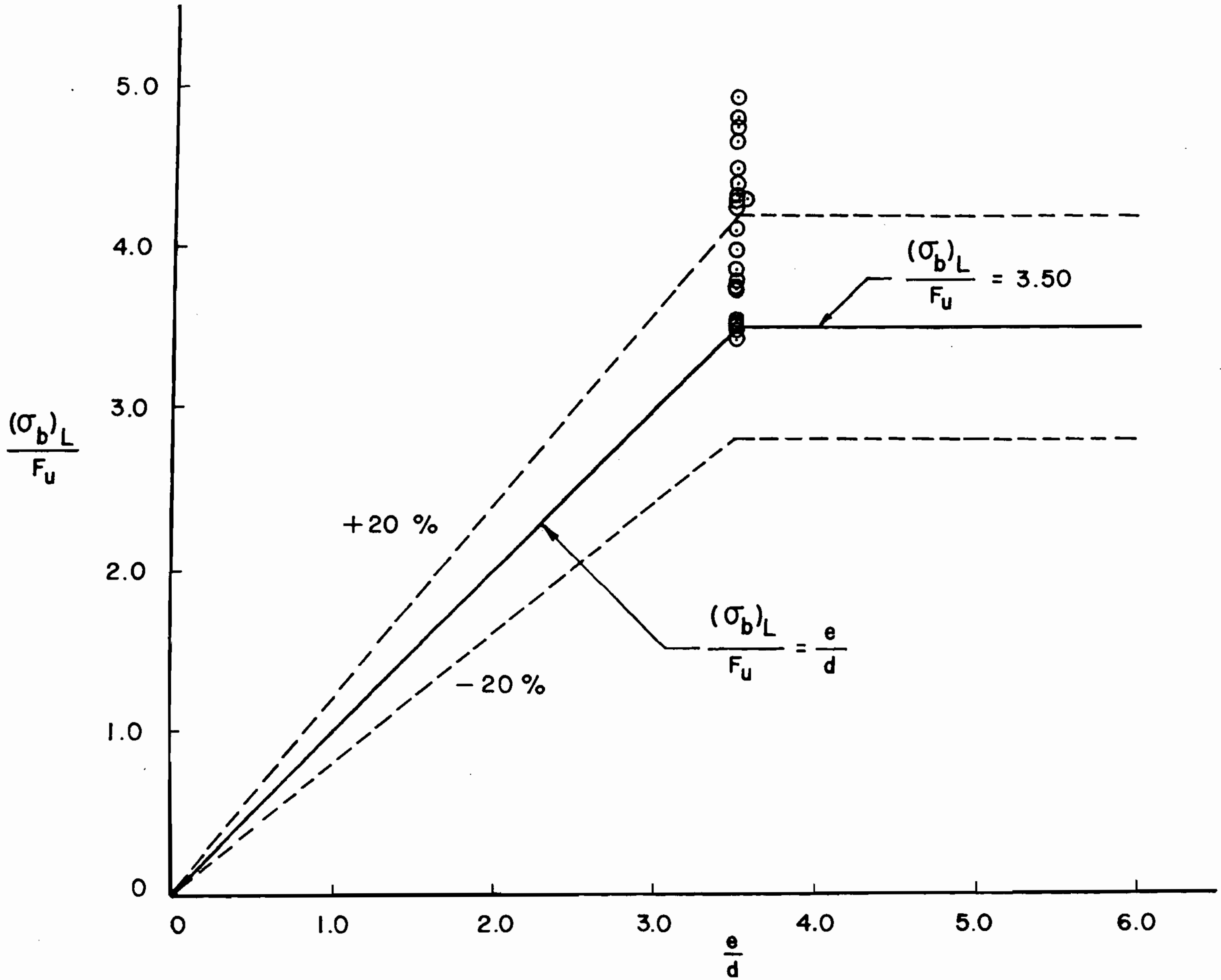

Figure 15. Correlation Between the predicted Ultimate Bearing Stress and Test Data Double Shear Connections with Washers, $\frac{F_u}{F_y} \geq 1.15$, $0.024 \leq t < \frac{3}{16}$ in.

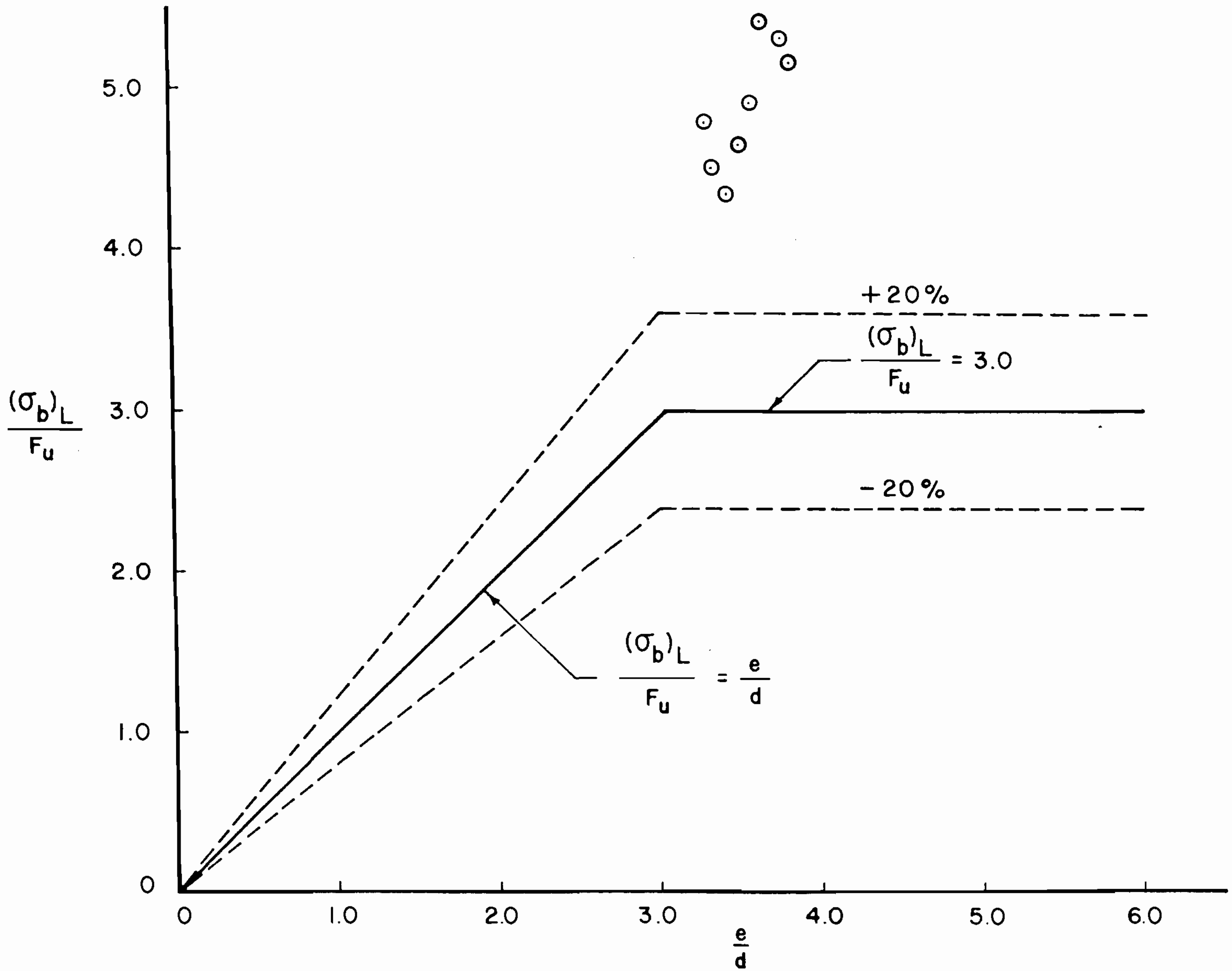

Figure 16. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections with Washers, $\frac{F_u}{F_y} < 1.15$, $0.024 \leq t < \frac{3}{16}$ in.

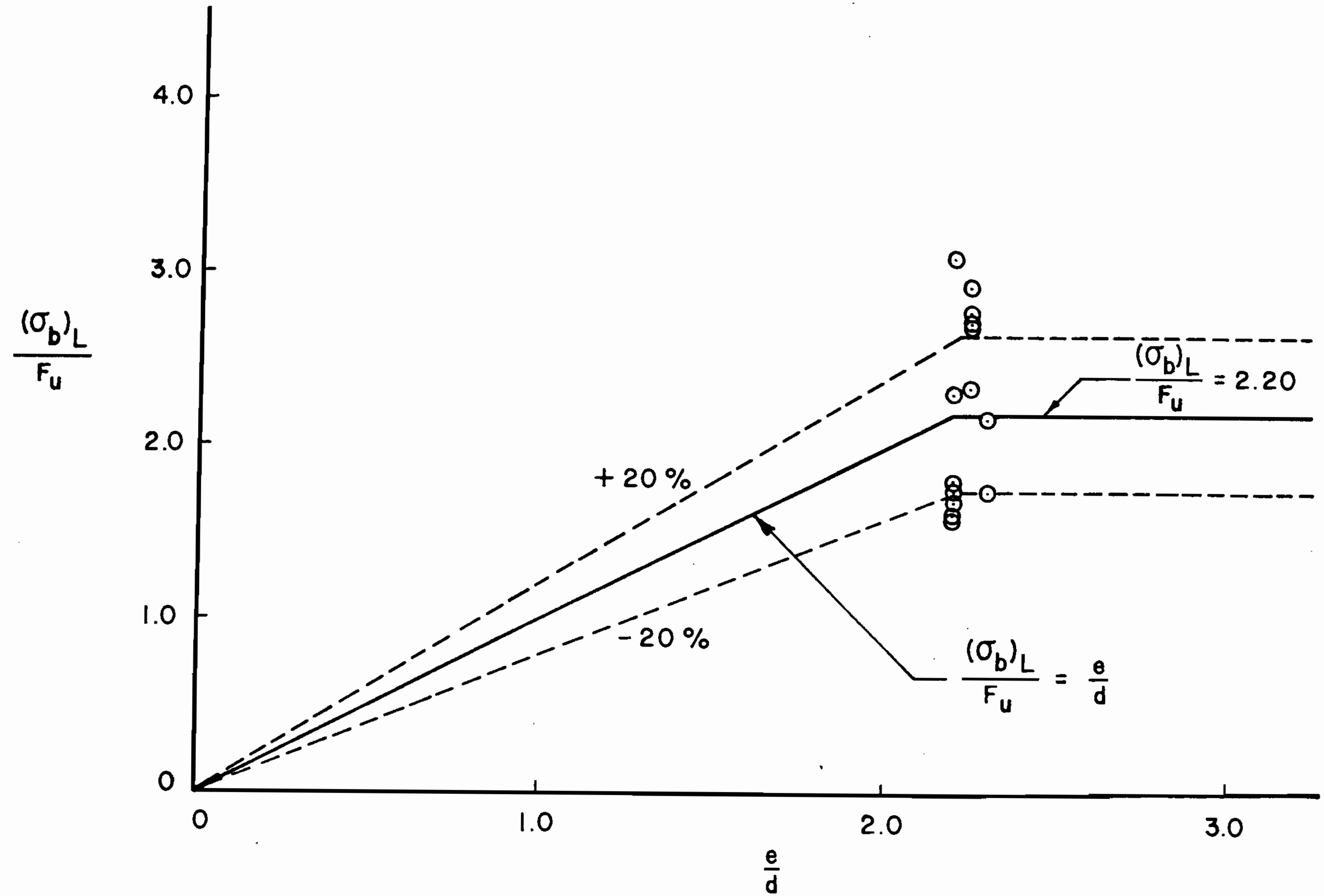

Figure 17. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Single Shear Connections without Washers, $\frac{F_u}{F_y} \geq 1.15$, $0.036 \leq t < \frac{3}{16}$ in.

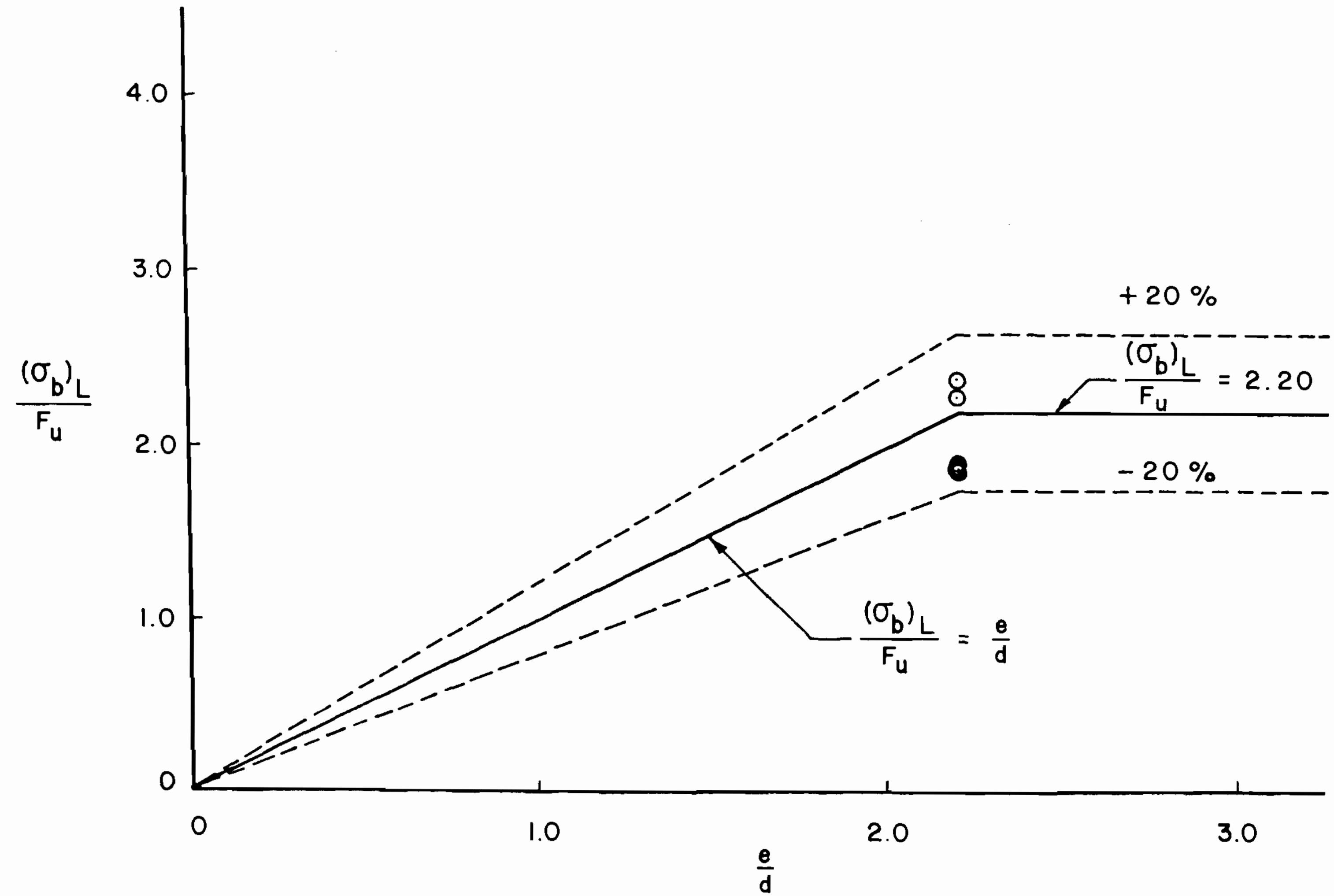

Figure 18. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Single Shear Connections Without Washers, $\frac{F_u}{F_y} < 1.15$, $0.036 \leq t < \frac{3}{16}$ in.

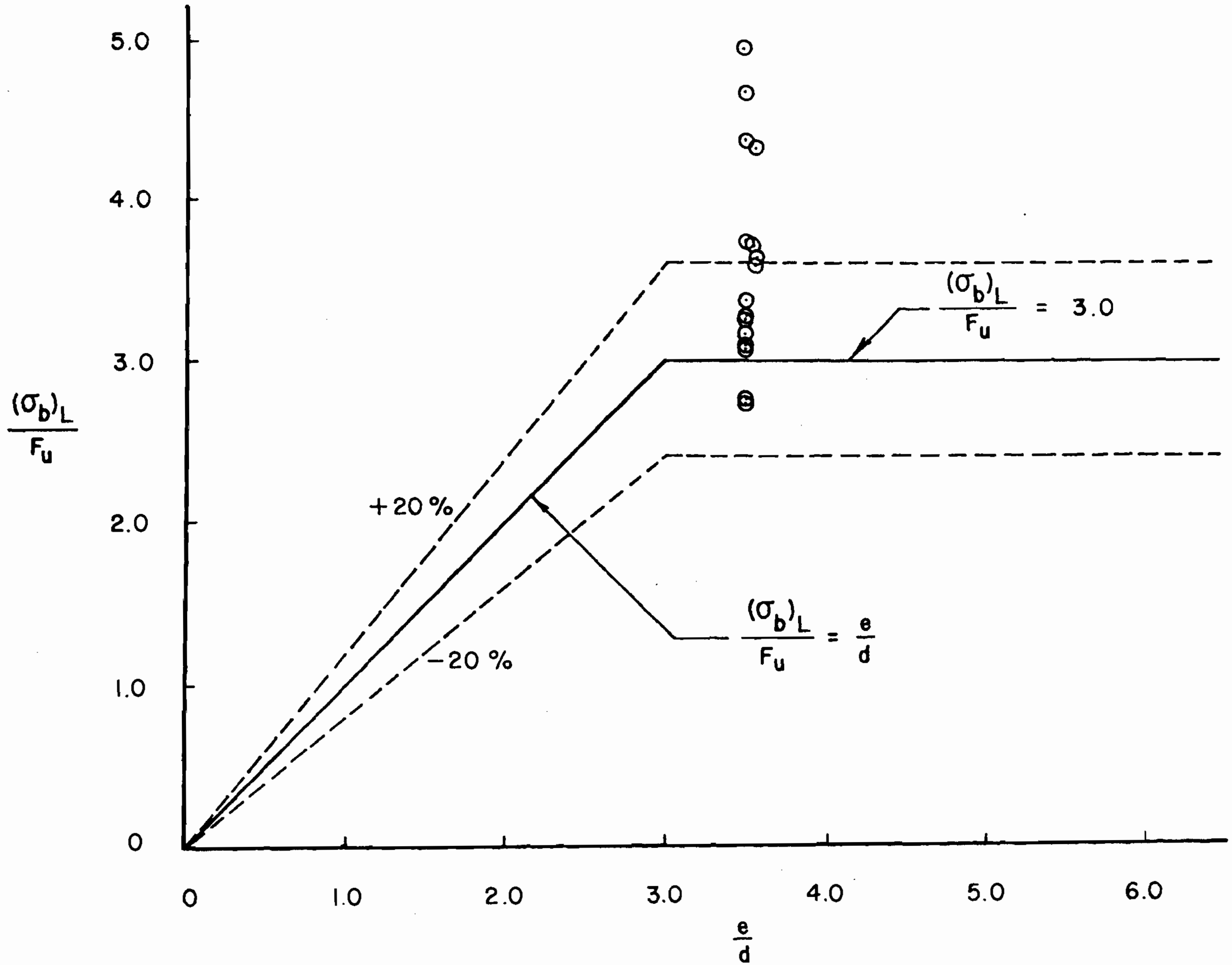

Figure 19. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections without Washers, $\frac{F_u}{F_y} \geq 1.15$, $0.036 \leq t < \frac{3}{16}$ in.

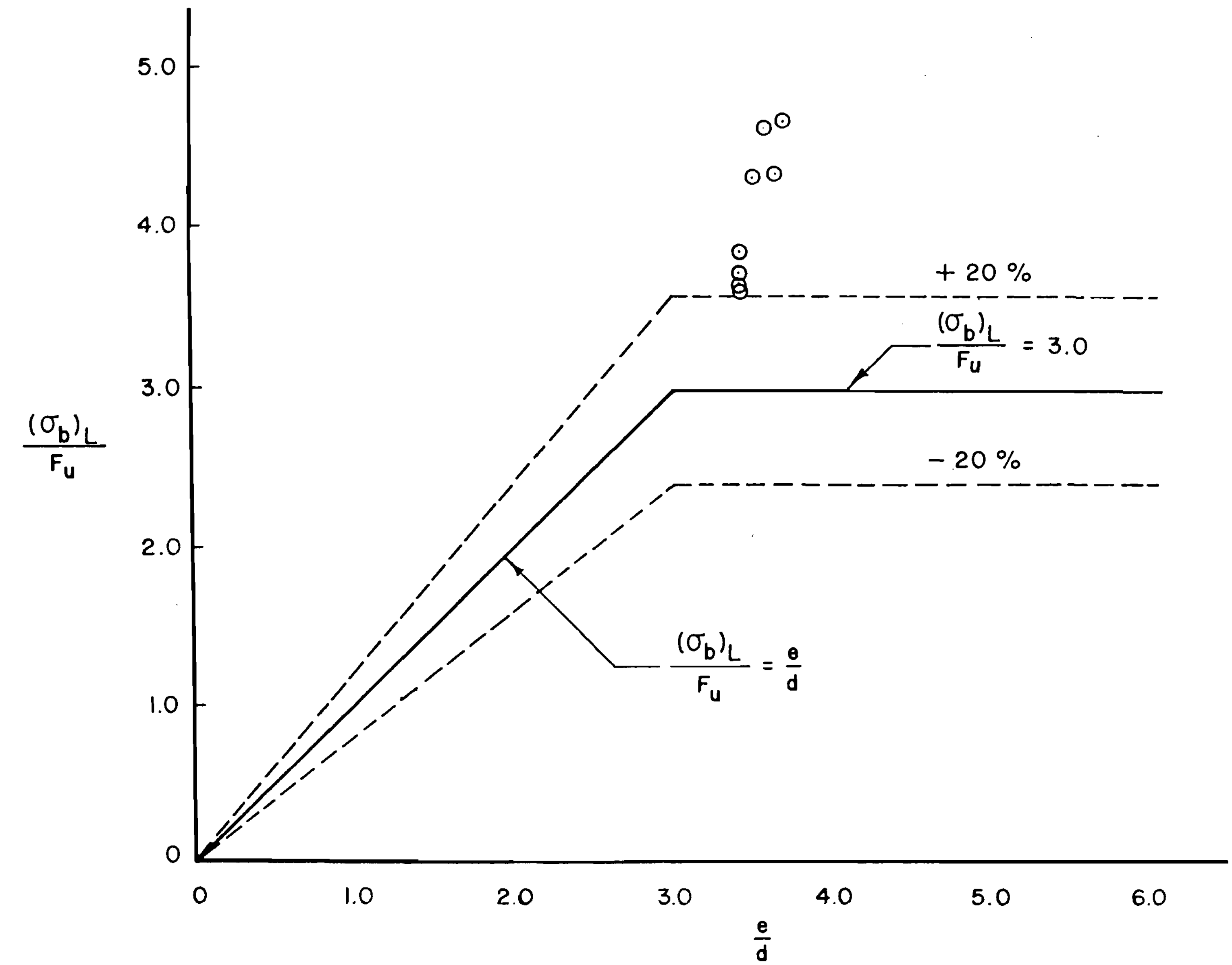

Figure 20. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections without Washers, $\frac{F_u}{F_y} < 1.15$, $0.036 \leq t < \frac{3}{16}$ in.

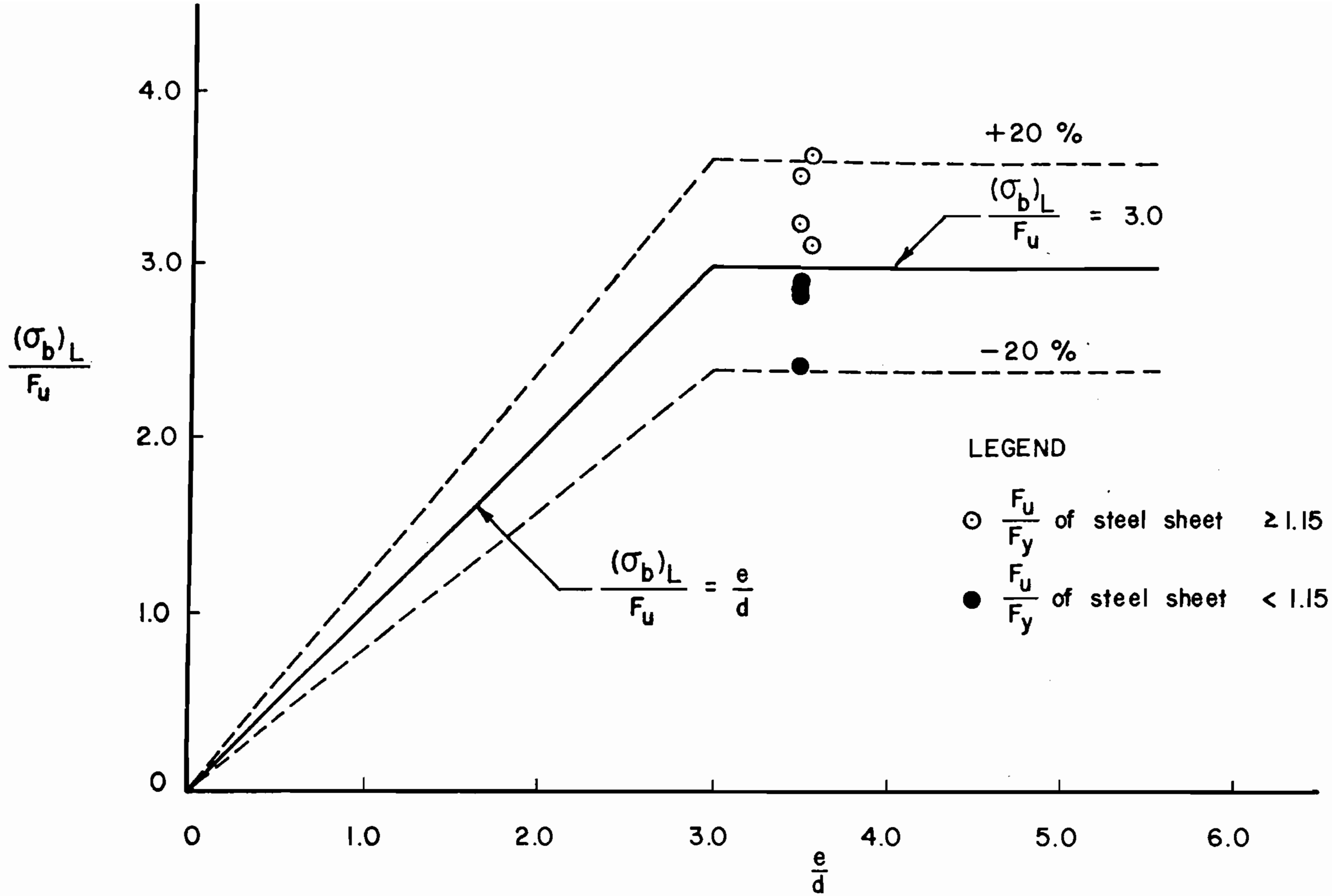

Figure 21. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Single Shear Connections with Washers, t < 0.024 in.

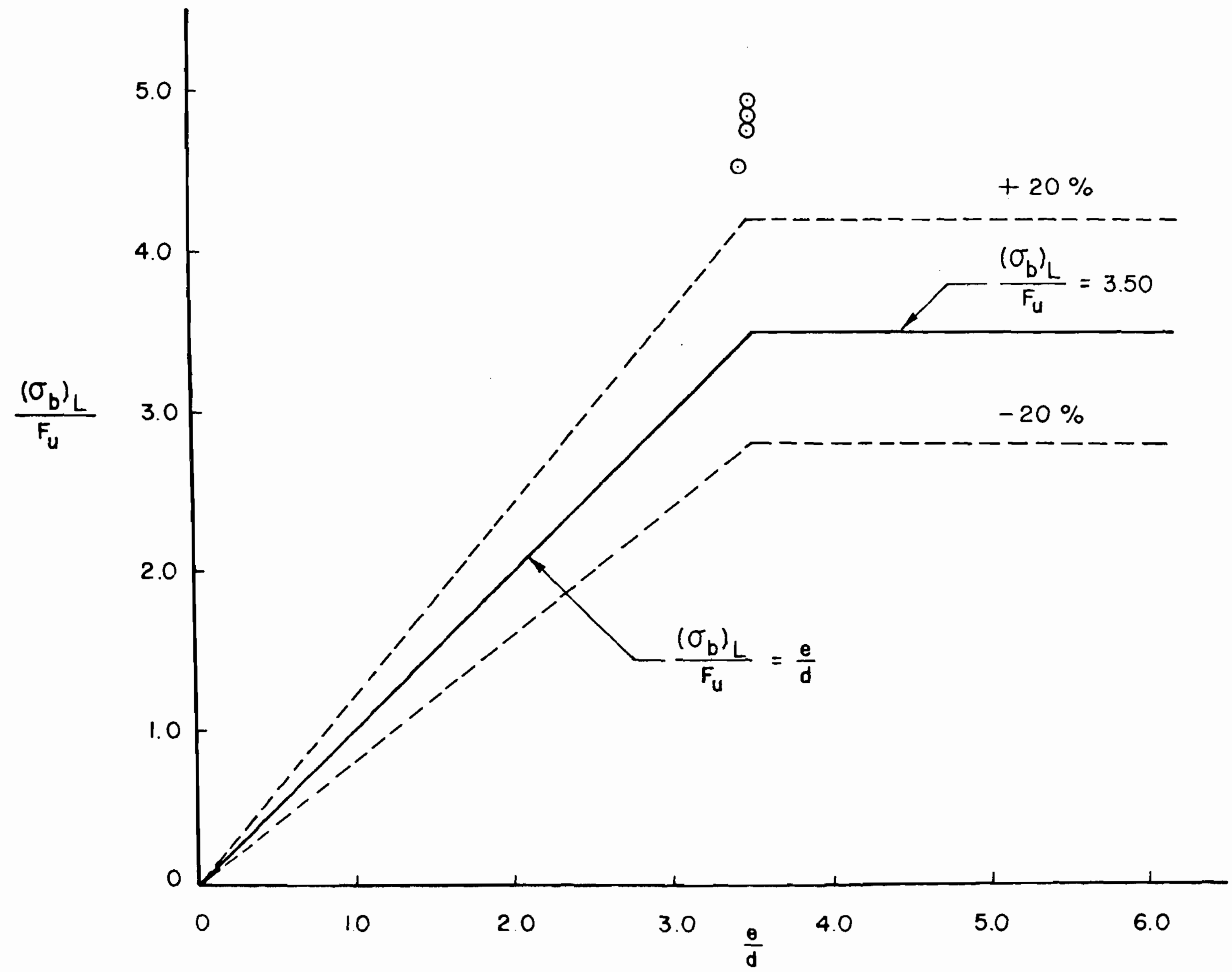

Figure 22. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections with Washers, $\frac{F_u}{F_y} \geq 1.15$, $t \leq 0.024$ in.

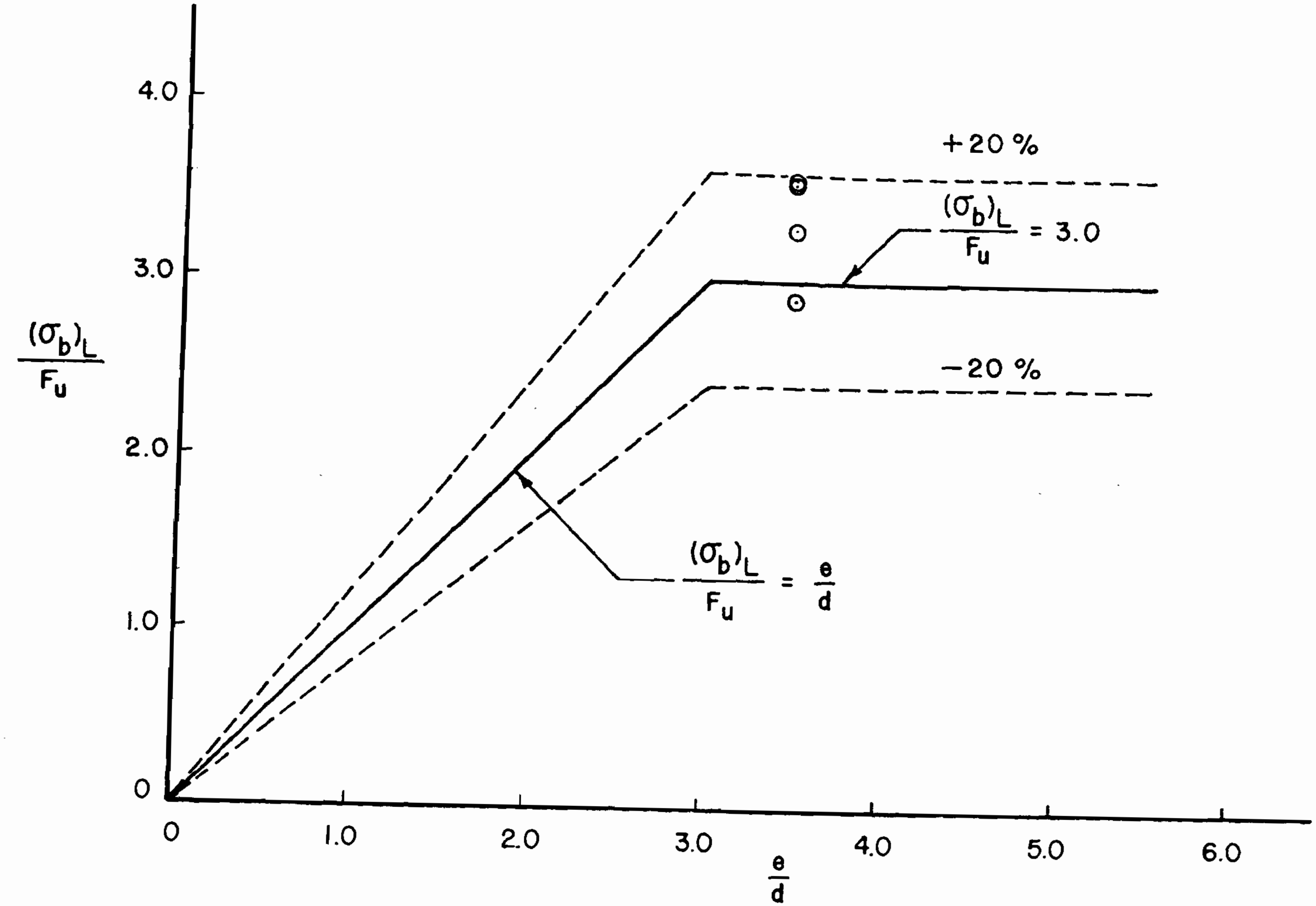

Figure 23. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections with Washers, $\frac{F_u}{F_y} < 1.15$, $t < 0.024$ in.

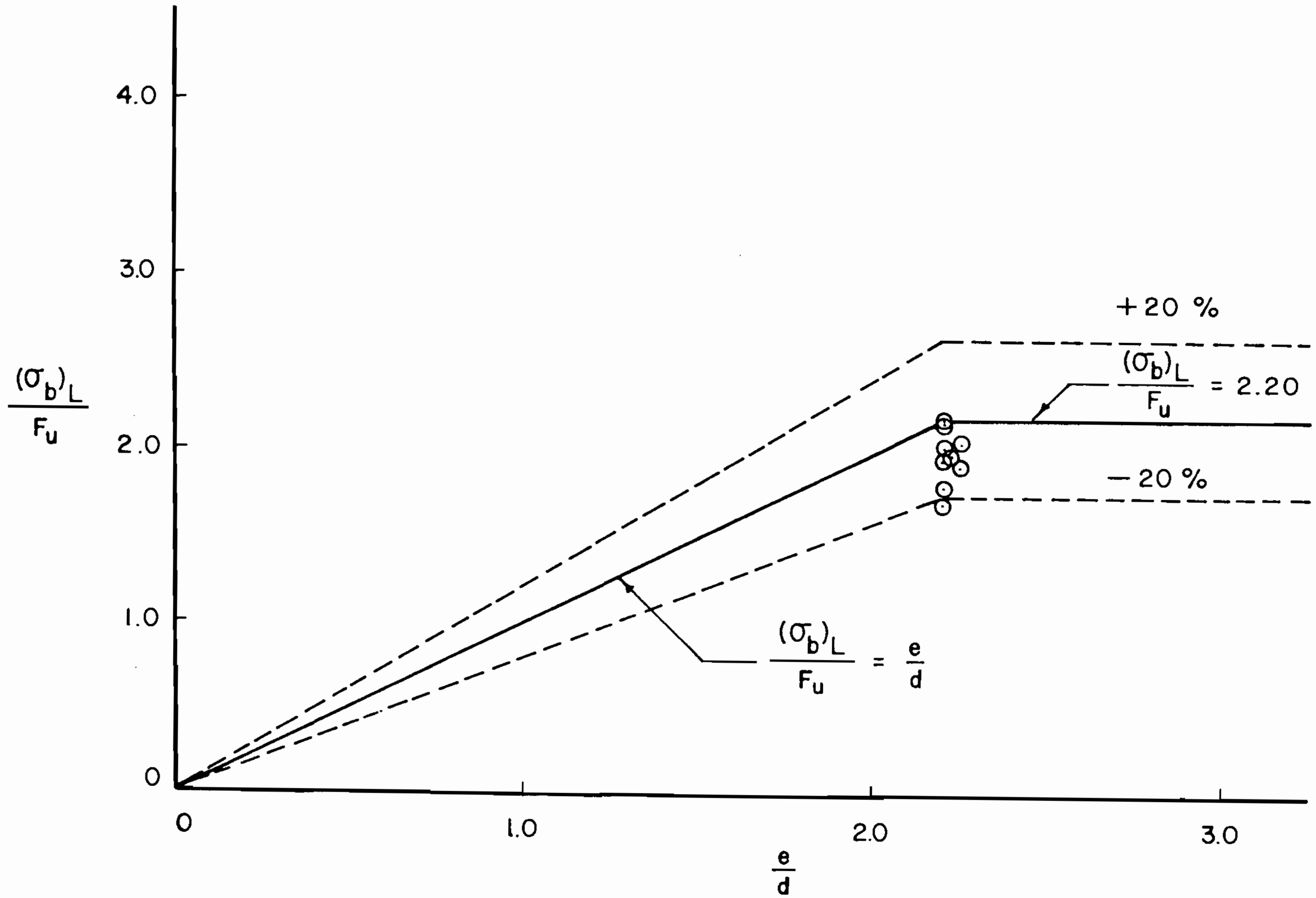

Figure 24. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Single Shear Connections without Washers, $\frac{F_u}{F_y} \geq 1.15$, $t \leq 0.036$ in.

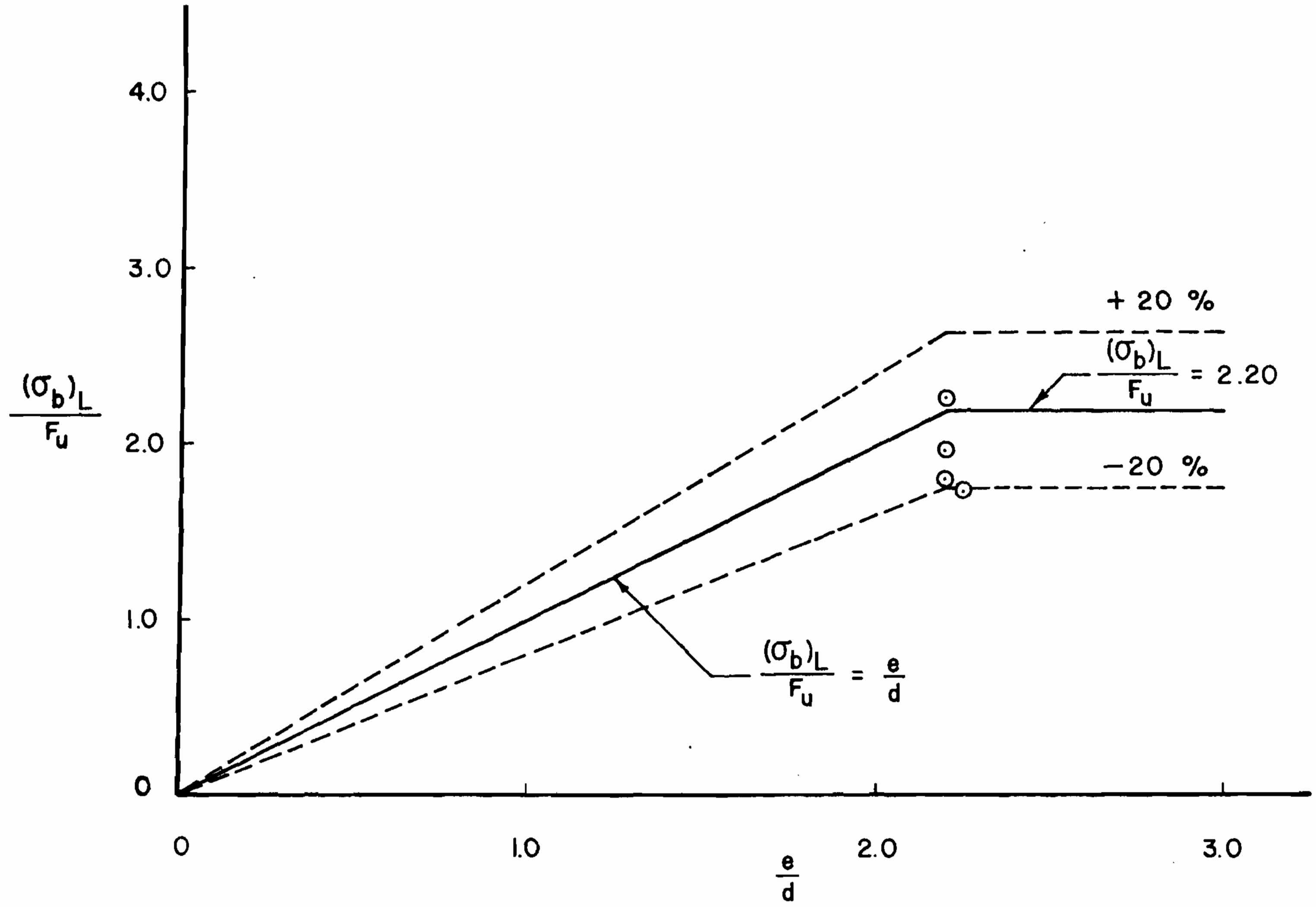

Figure 25. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Single Shear Connections without Washers, $\frac{F_u}{F_y}$ <1.15, t < 0.036 in.

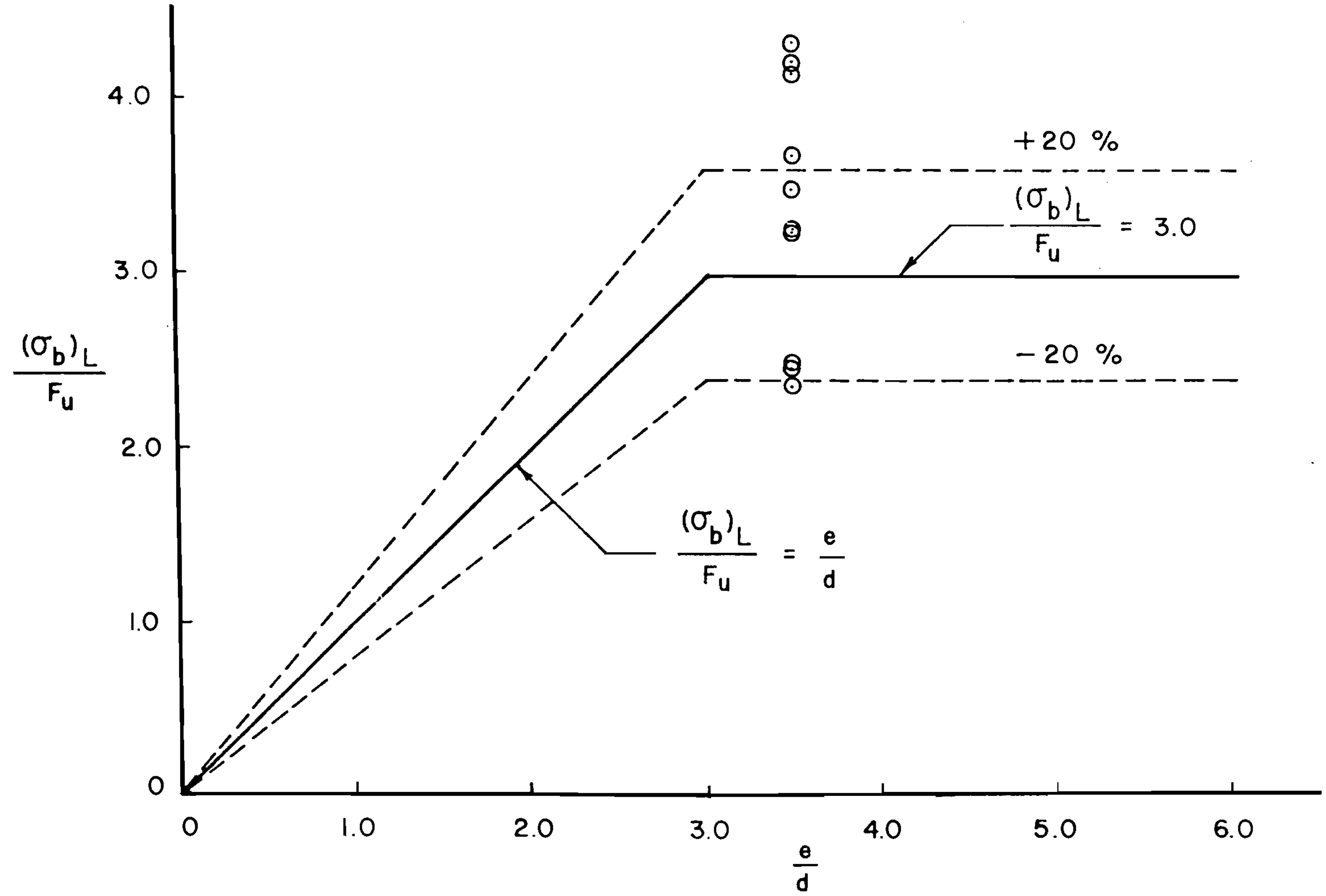

Figure 26. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections Without Washers, $\frac{F_u}{F_y} \geq 1.15$, t < 0.036 in.

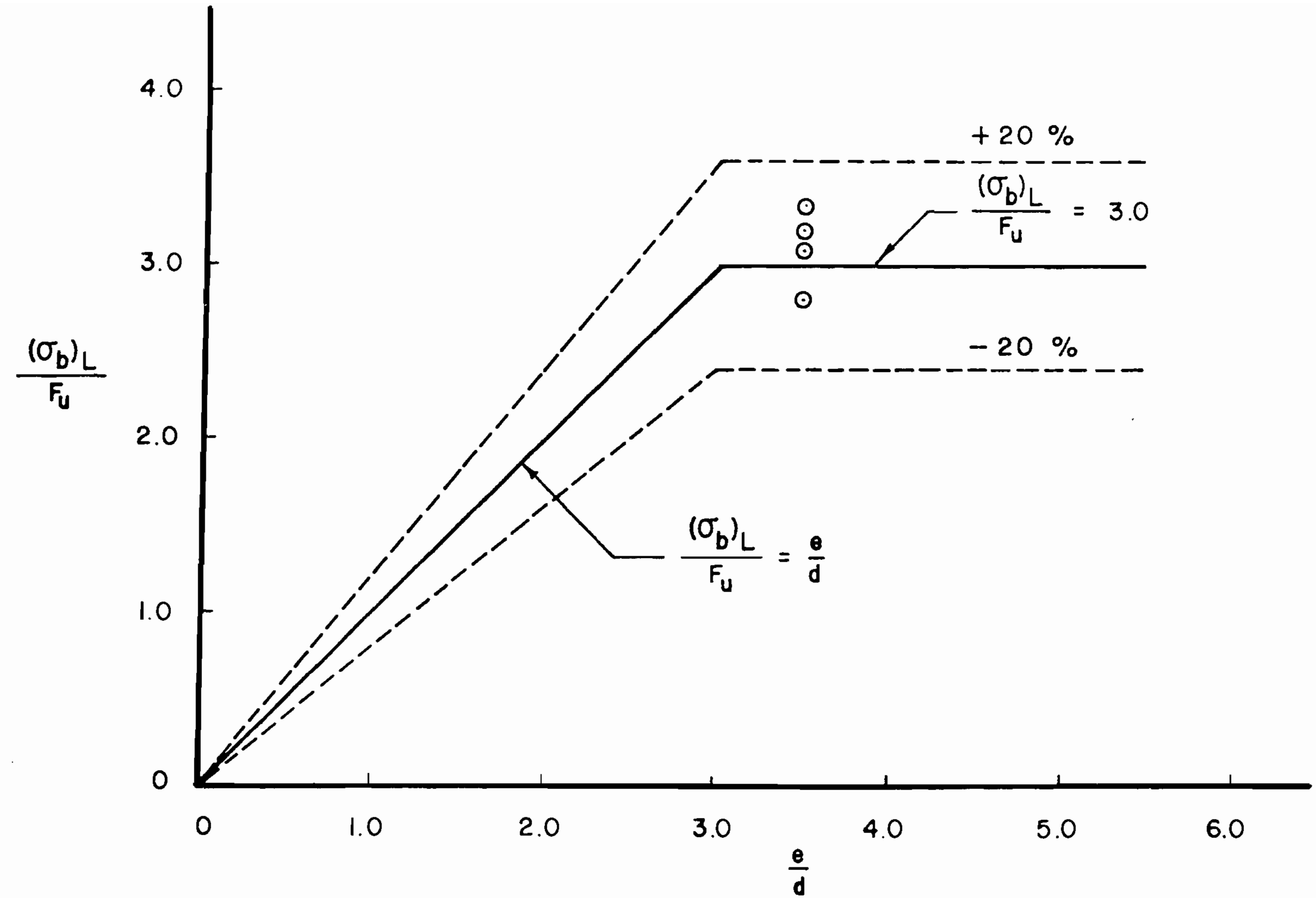

Figure 27. Correlation Between the Predicted Ultimate Bearing Stress and Test Data Double Shear Connections without Washers, $\frac{F_u}{F_y} < 1.15$, $t < 0.036$ in.

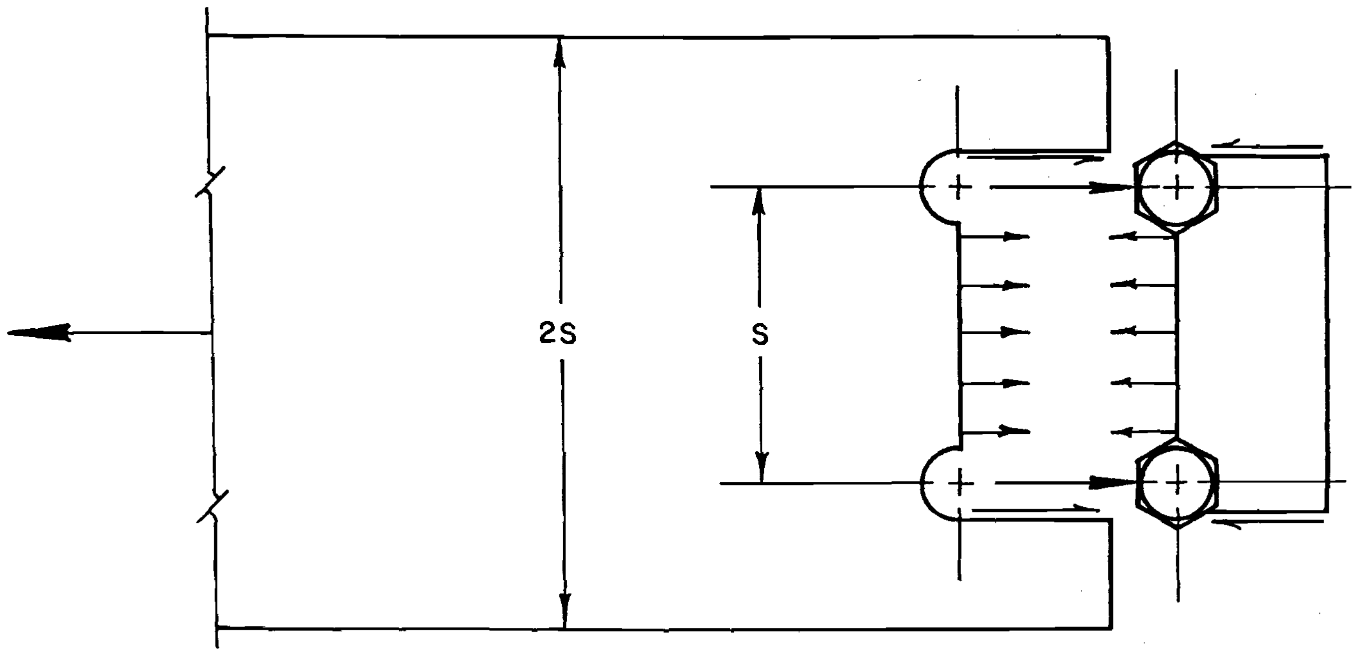

Figure 28. Failure Mode Governed by Combined Shear and Tension